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FUEL ELEMENTS FOR THE ORGANIC MODERATED REACTOR EXPERIMENT

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

NAA-SR-1934
METALLURGY AND CERAMICS
82 PAGES

FUEL ELEMENTS FOR THE ORGANIC MODERATED REACTOR EXPERIMENT

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ATOMICS INTERNATIONAL
A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA

CONTRACT: AT(04-3)-88
ISSUED: DECEMBER 15, 1957

DISTRIBUTION

This report has been distributed according to the category "Metallurgy and Ceramics" as given in "Standard Distribution Lists for Unclassified Research and Development Reports" TID-4500 (13th Edition), January 15, 1957. A total of 580 copies was printed.

ACKNOWLEDGMENT

The authors wish to gratefully acknowledge the assistance of persons in the Fuel Element Fabrication Development Group.

For help on specialized problems outside of this group, thanks are extended to D. B. Miller, W. F. Anderson, N. C. Miller, H. Schlein, R. O. Williams, Jr., S. Sudar, and S. Bain.

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ABSTRACT

The development of a floating-plate-type fuel element for the Organic Moderated Reactor Experiment is described. The fuel element is a stainless-steel box containing 16 active fuel plates which "float" in longitudinal grooves. The floating plates minimize distortion caused by the large temperature differences experienced with the use of an organic coolant. The fuel plates consist of a core of highly enriched UO_2 particles uniformly dispersed in a stainless-steel matrix clad with stainless steel.

Techniques for fabricating the fuel plates are also described. The fuel plate is fabricated by hot- and cold-rolling a 3/8-inch thick sandwich assembly into the 0.030-inch thick fuel plate. The sandwich consists of a stainless steel-UO_2 compact encased by a frame and two cover plates of stainless steel.

Development of a non-destructive gage to detect variations of UO_2 content in the fuel core of the finished plate and a method of attaching five-mil-diameter thermocouples to five-mil-thick fuel core cladding are noted.

I. INTRODUCTION

The Organic Moderated Reactor Experiment (OMRE) was initiated as a joint venture by Atomics International and the Atomic Energy Commission to obtain information about the various performance parameters of organic moderator-coolants. Specific information was needed on the rate of thermal and radiation damage to a hydrocarbon-type organic and the effect of decomposition of the coolant-moderator on the operation of the reactor. It was also necessary to develop an adequate purification system for the damaged hydrocarbon.

A reactor moderated by an organic fluid has the advantages of a water system, that is, small size and good nuclear characteristics, without the problems of a high-pressure primary coolant circuit and a uranium-coolant reaction hazard. The safety features of an organic moderator are among its principal advantages. An organic moderator would permit the use of a low-pressure coolant system with no catastrophic chemical incompatibilities between the coolant and uranium or between the coolant and the water of the secondary coolant circuit and with no unusual corrosion problems. Because the moderator is a fluid, the reactor at operating temperatures would have a negative temperature coefficient of reactivity which would resist undesired increases in temperature and power level.

The nuclear characteristics of an organic moderator would permit a compact core with good neutron economy. The organic fluid becomes only slightly radioactive, which makes the entire heat transfer system relatively accessible.

Highly-enriched uranium oxide was chosen for the fuel of the hydrocarbon-cooled, -moderated, and -reflected experimental thermal reactor. A fuel element type was selected on which previous plate fabrication experience had been accrued. The heat transfer characteristics of the organic coolant are less desirable than water for which the element had been designed. Consequently, it was necessary to develop a fuel-element assembly suitable for the organic coolant.

The fuel element, Fig. 1, consists of a stainless-steel box containing thin, flat plates composed of highly-enriched uranium oxide in a stainless-steel matrix clad with stainless steel.

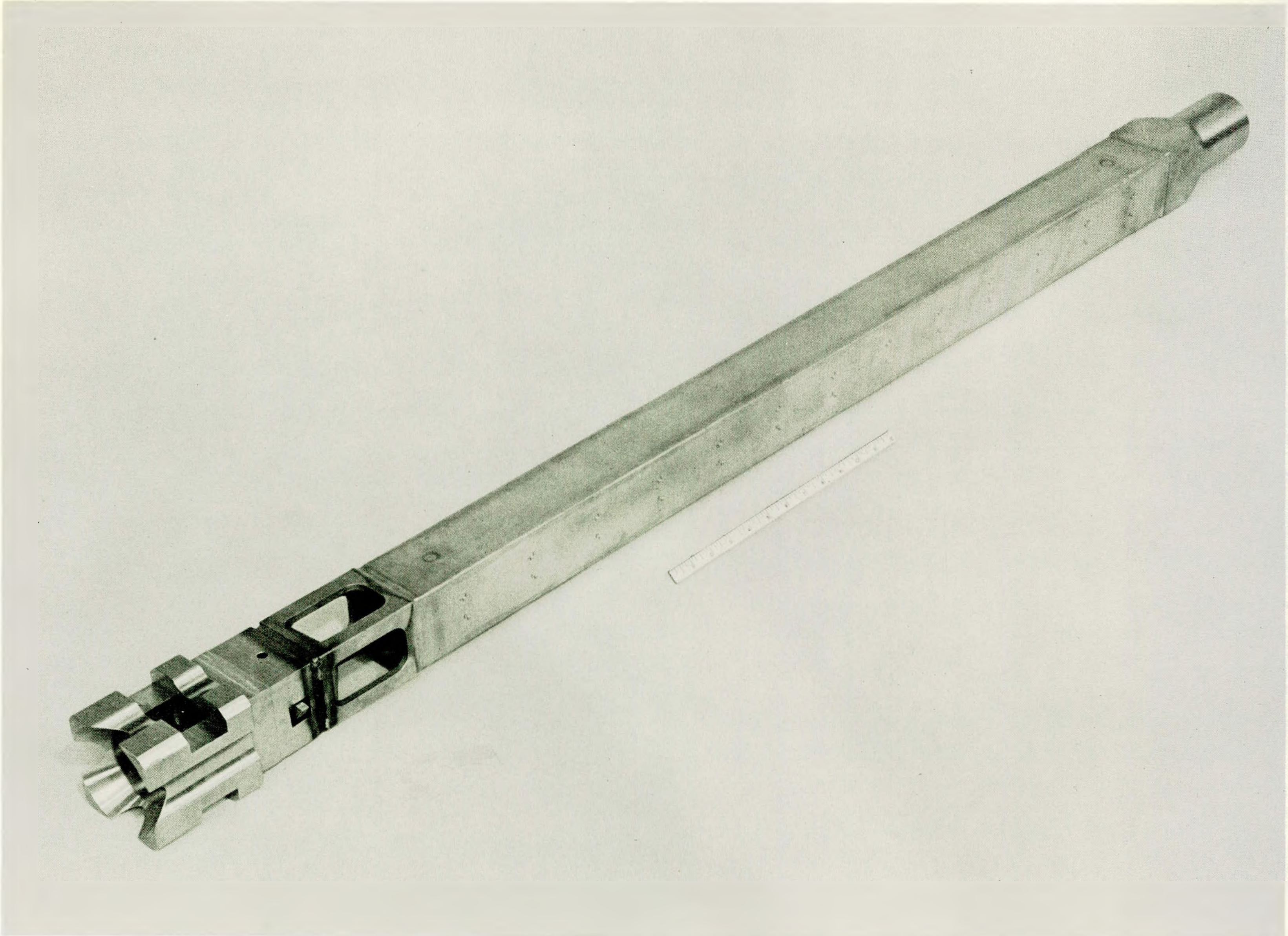


Fig. 1. OMRE Fuel Element

The reactor was designed to have a maximum thermal power level of 16,000 kilowatts. Figure 2 is a cutaway drawing of the reactor. The core normally contains 25 fuel elements with provisions for 11 more should the need arise. The fuel elements are spaced on 4-1/2-inch centers by two grid plates within the 4.5-foot inside diameter by 28-foot-high core tank. The polyphenyl moderator-coolant is pumped through the core at the rate of 7,200 gpm and at a pressure of 300 psi. The coolant at an operating temperature of 500° to 700° F is circulated through an airblast heat exchanger for heat removal. An auxiliary coolant loop is provided for emergency removal of afterglow heat.

The reactivity of the reactor is controlled by 12 rack-and-pinion driven, boron carbide control-safety rods. A still-type purification system continuously removes decomposition and polymerization products from the coolant-moderator.

Table I outlines the operating parameters of the reactor core.

TABLE I

REACTOR CORE CHARACTERISTICS

Average Thermal Flux	5×10^{13}
Loading (25 Elements)	20.6 kg U^{235}
Burnup	11.2% U^{235}
Specific Power	776 kw/kg U^{235}

II. OMRE FUEL ELEMENT

A. ELEMENT DESCRIPTION

The fuel element is illustrated in Fig. 1. It consists of a fuel box to which castings are welded to enable the element to be installed in the reactor grid plates. One of the castings on the upper end of the fuel element serves to divert the flow of the coolant from the fuel element into the upper plenum chamber of the reactor. A casting welded to the diverter aligns the fuel element in the upper grid plate of the reactor and contains a latching mechanism which locks the element into that

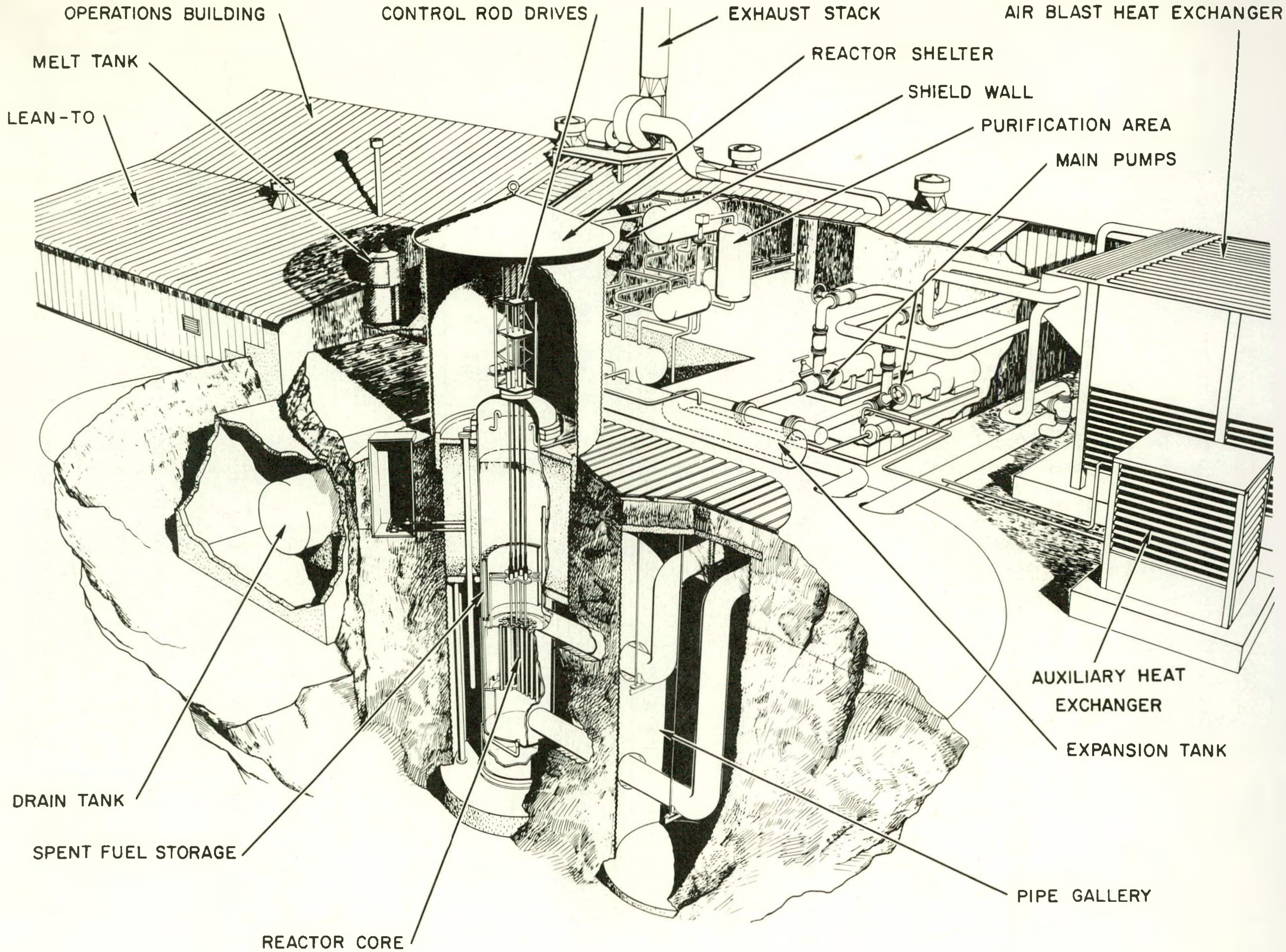


Fig. 2. OMRE Reactor

grid plate. The actuating shaft of the latch mechanism also attaches to the tool used to install and remove the element from the reactor. A hollow casting through which the coolant enters the fuel element is welded to the lower end of the fuel box. The casting fits into the lower grid plate and vertically aligns the fuel element. The physical characteristics of the fuel element are summarized in Table II.

TABLE II

OMRE FUEL ELEMENT

Type	Plate
Active Dimensions of Plate	0.02 in. x 2.5 in. x 36 in.
Over-all Dimensions of Plate	0.03 in. x 2.8 in. x 37 in.
Plate Cladding	304 Stainless Steel
Fuel Core Material	25% UO_2 - 75% Stainless Steel
Uranium Enrichment	Full
Element Assembly Type	Box
Number of Fuel Plates	16
304 Stainless Steel Side Plates (2)	0.050 in. thick
304 Stainless Steel End Plates (2)	0.030 in. thick
Element Construction	Mechanical Assembly

B. FUEL BOX DESCRIPTION

A cutaway drawing of the fuel box is shown in Fig. 3. The stainless-steel fuel box contains 16 active fuel plates. The fuel plates contain a 20-mil-thick core consisting of fully enriched UO_2 particles uniformly dispersed in a matrix of stainless steel. The fuel core is clad with a five-mil thickness of stainless steel metallurgically bonded to the core and to the stainless-steel frame around the core. Figure 4 shows a cross section of a fuel plate.

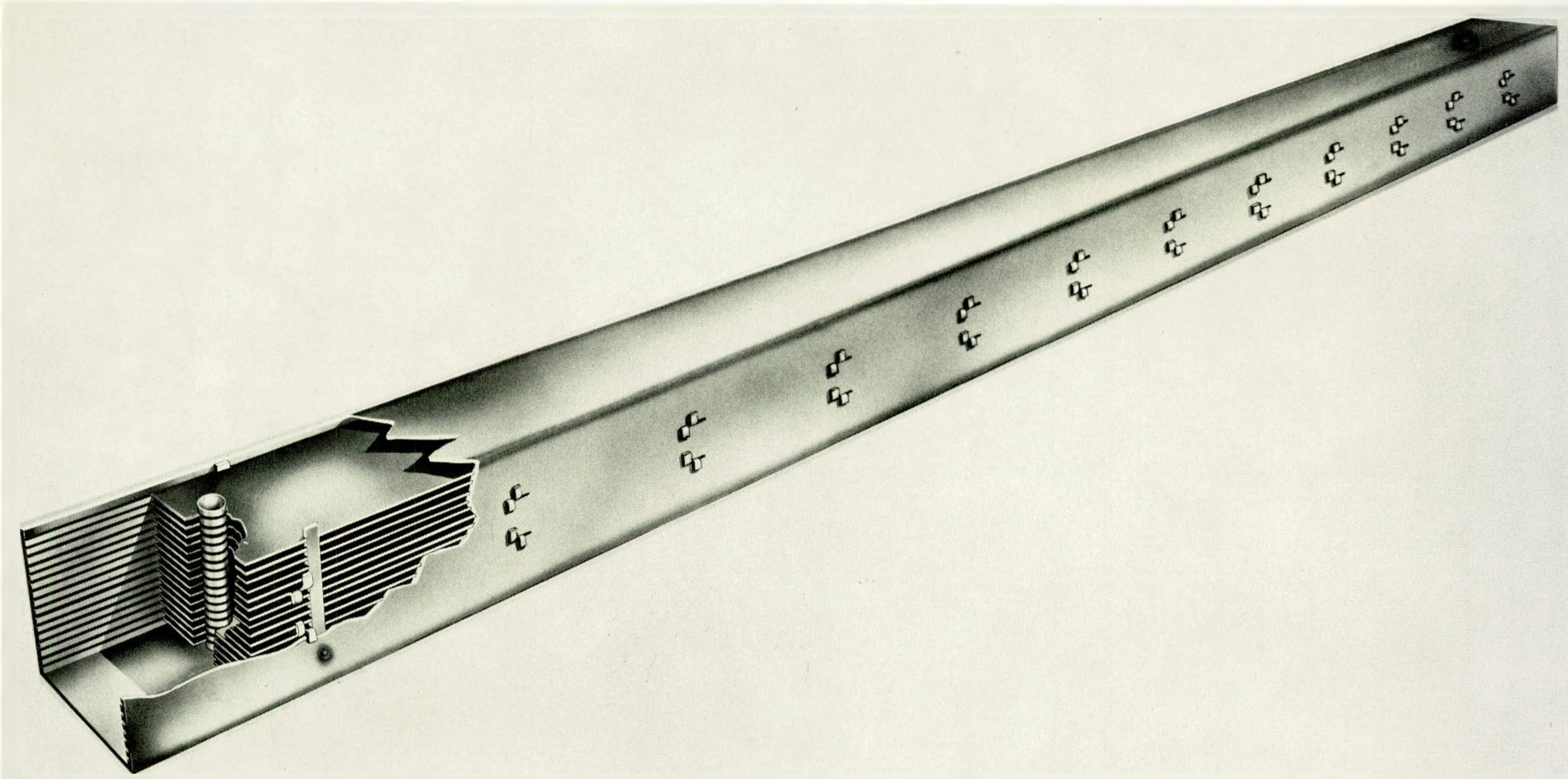


Fig. 3. OMRE Fuel Box

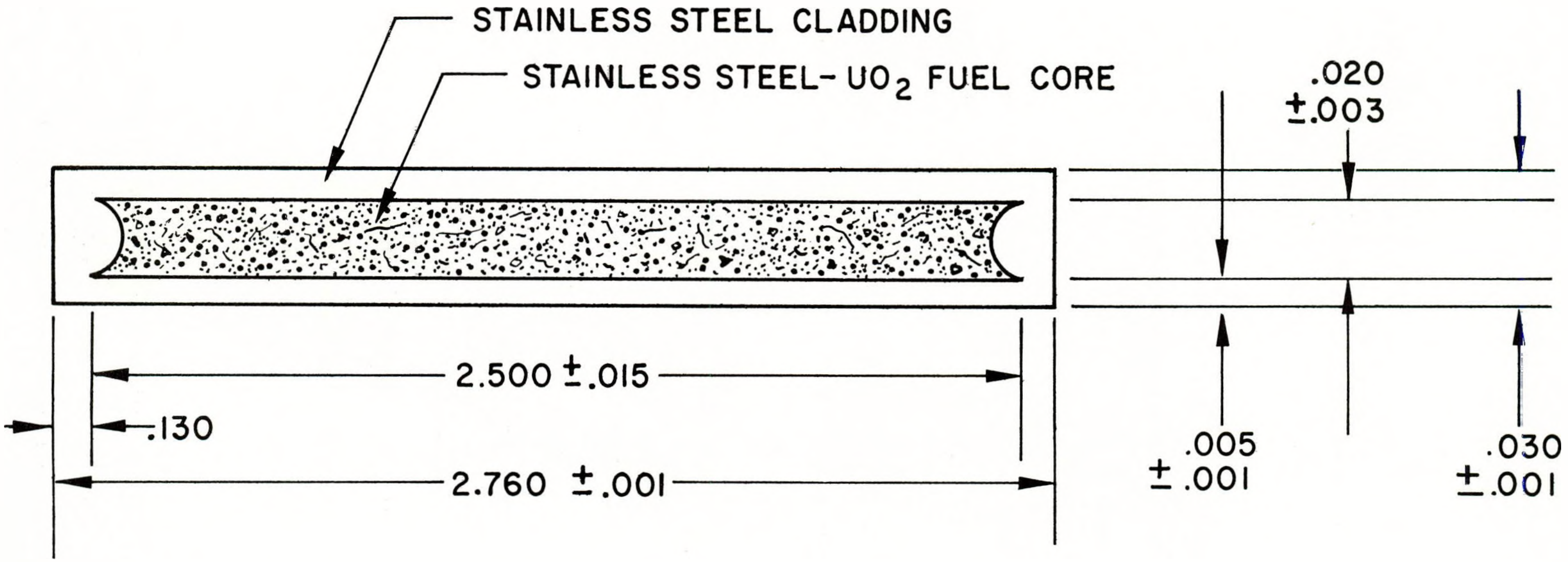


Fig. 4. Cross Section of OMRE Fuel Plate

The fuel box consists of two end plates and two side plates seam-welded together at the corners to form a box (Fig. 3). The 50-mil-thick side plates are longitudinally grooved to a depth of 30 mils to receive and space the fuel plates with 134-mil channels between plates. The fuel plates "float" in the longitudinal grooves and are held stationary near the inlet end of the box by a retaining bar welded to the side plate which engages notches in the fuel plates. The other end of the fuel plate is free to move within side plate grooves as required by differential thermal expansion of the components. Spacer pins are installed near each end of the fuel box to engage slots in each end of the fuel plates. Sufficient clearance has been provided between the bottom of the side plate groove and the fuel plate to allow transverse expansion of the plate. Two of the fuel plates are equipped with 26 split tabs each, which protrude through corresponding slots in the side plates and are bent over. These prevent the side plates of the fuel box from bowing under internal pressure. The various components of the fuel element are shown in Fig. 5.

III. FUEL PLATE CORE MATERIALS

The stainless steel-UO_2 fuel combination was selected on the basis of prior experience with this particular type of fuel. The choice was guided by the following basic principles employed in other successful stainless steel-UO_2 fuel elements:

1) The use of highly-enriched U^{235} fuel to permit a compact core which reduces the size of the experimental reactor.

2) Uniform distribution of discrete particles of fuel in the matrix to diminish dimensional instability due to radiation damage.

3) The use of thin plate-type construction to give a high surface-to-volume ratio for good heat transfer characteristics.

A. FUEL

A high-fired fully-enriched uranium oxide (more than 90 per cent enrichment) was selected for the fuel. The UO_2 was obtained from the Union Carbide Nuclear Corporation at Oak Ridge which derived it from uranium hexafloride. The UO_2 was high fired for a minimum of one hour at 1700° to 1800° C. The particle size

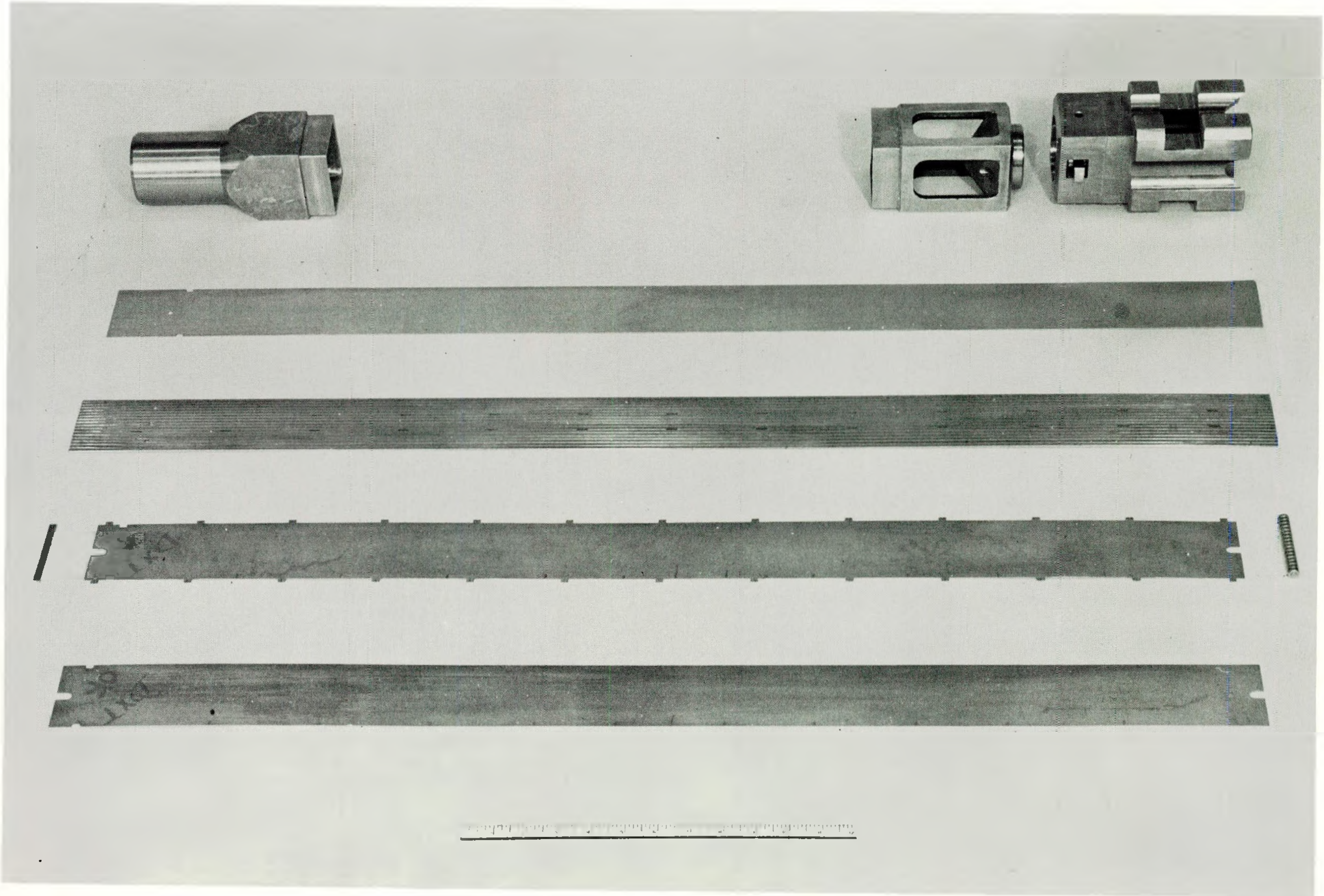


Fig. 5. OMRE Fuel Element Components

was such that 100 per cent of the powder passed through 170-mesh screen and was retained on a 325-mesh screen (88 to 44 micron particle size range).

From the point of view of powder metallurgy practices, UO_2 of a small particle size would be distributed through the matrix more uniformly after the rolling operation than would the relatively large UO_2 particles that were used for the fuel. However, the larger UO_2 particles were chosen on the basis of irradiation data which indicated that fission fragments are better contained by larger particles as contrasted to small particles.[1]

B. MATRIX

Type 304 stainless-steel powder which was modified to contain a minimum of 2 per cent silicon to facilitate the powder manufacture was used for the fuel matrix.

Table III is a typical sieve analysis of the stainless-steel powder. The powder particles were irregularly shaped to obtain a high packing density and to provide a large number of contact points for the sintering operation. The irregularly shaped powder particles were produced through the use of the atomization process.[2]

TABLE III

SIEVE ANALYSIS OF STAINLESS-STEEL POWDER

Sieve	Screen Size Opening, Microns	% Powder Retained on Screen
100	149	1.9
140	105	23.9
200	74	26.1
325	44	17.0
-325		31.0
		100.00

IV. OMRE FUEL ELEMENT FABRICATION

The fuel core for the fuel plates was fabricated by powder metallurgy techniques which consisted of pressing and sintering a blended mixture of uranium oxide and stainless-steel powders. The pressed compact was placed in a stainless-steel "sandwich" which was hot and cold rolled to produce the thin fuel plate. The plates were machined to size and assembled into the fuel box. The fuel element was completed by welding adapter fittings to each end of the fuel box.

Figure 6 is a flow sheet of the fabrication of the sandwich assembly and Fig. 7 is a flow sheet of the fabrication techniques used to produce the fuel plate from the sandwich assembly.

The following is a description of the various steps that are necessary to fabricate an OMRE fuel element.

A. CORE FABRICATION

Sufficient stainless-steel and UO_2 powders were blended in one batch to produce 18 finished compacts, the loading for one fuel element plus a process scrap allowance. A ratio of three parts of stainless-steel powder was blended with approximately one part of UO_2 powder for one hour. A die with a 2.387-inch by 3.860-inch cavity was loaded with 240 grams of blended powder and was pressed at 49 tons per square inch to produce a core compact approximately 1/4-inch thick. The enclosed and vented hydraulic press and powder loading glove box are shown in Fig. 8.

The "green" compact was sintered in a dry hydrogen atmosphere for 1-1/2 hours at 2150° F.

B. SANDWICH ASSEMBLY

The sandwich consisted of two 1/16-inch thick by 4-inch by 6-inch stainless-steel cover plates, one of which had been welded to each side of the stainless-steel "picture frame" that contained the sintered compact. The 4-inch by 6-inch picture frame contained a rectangular opening to receive the compact and a vent hole on one end to permit trapped gases to escape during the hot-rolling process. The cover plates and the picture frame were degreased and then sand-blasted

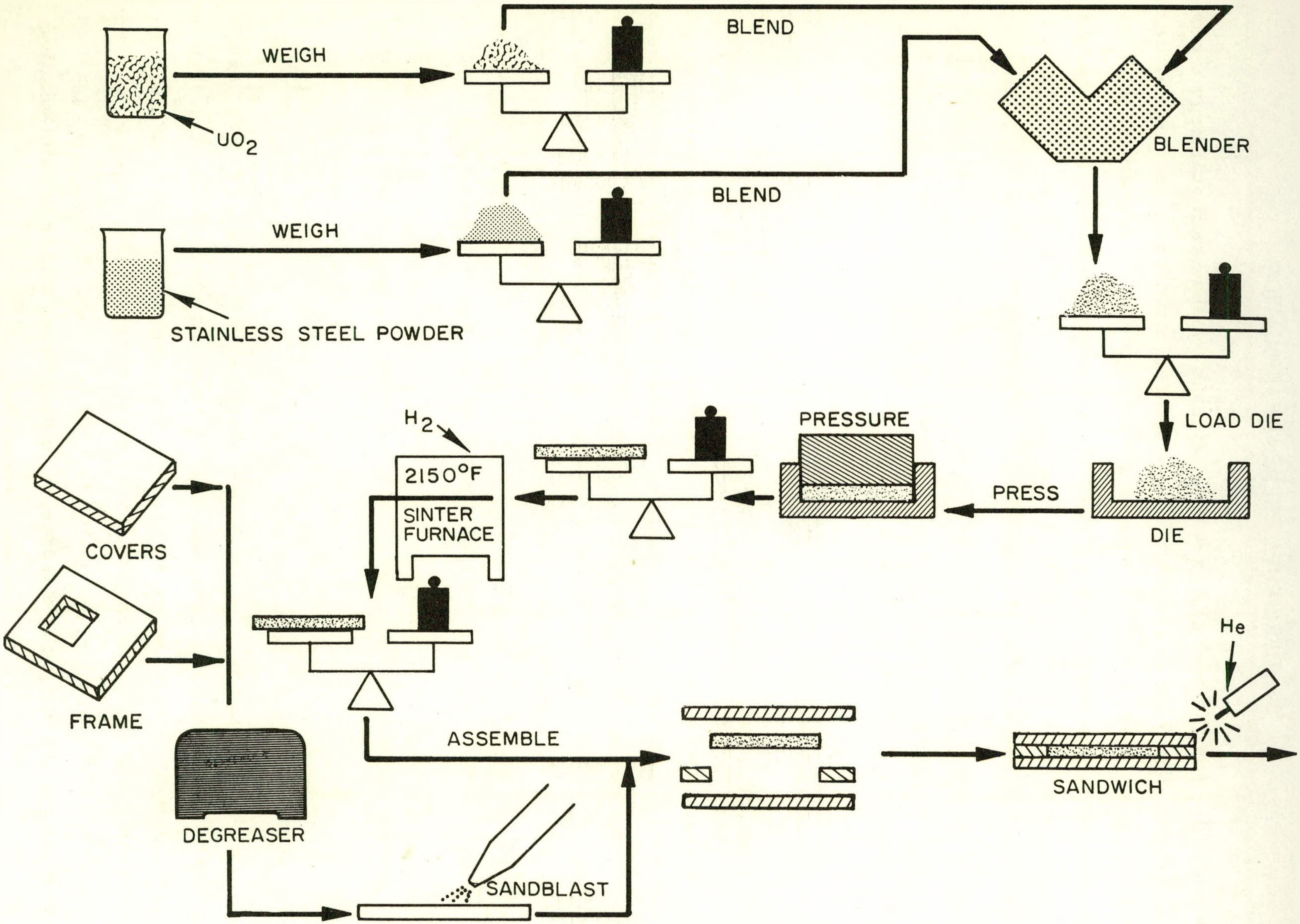


Fig. 6. OMRE Fuel Compact and Sandwich Fabrication Flowsheet

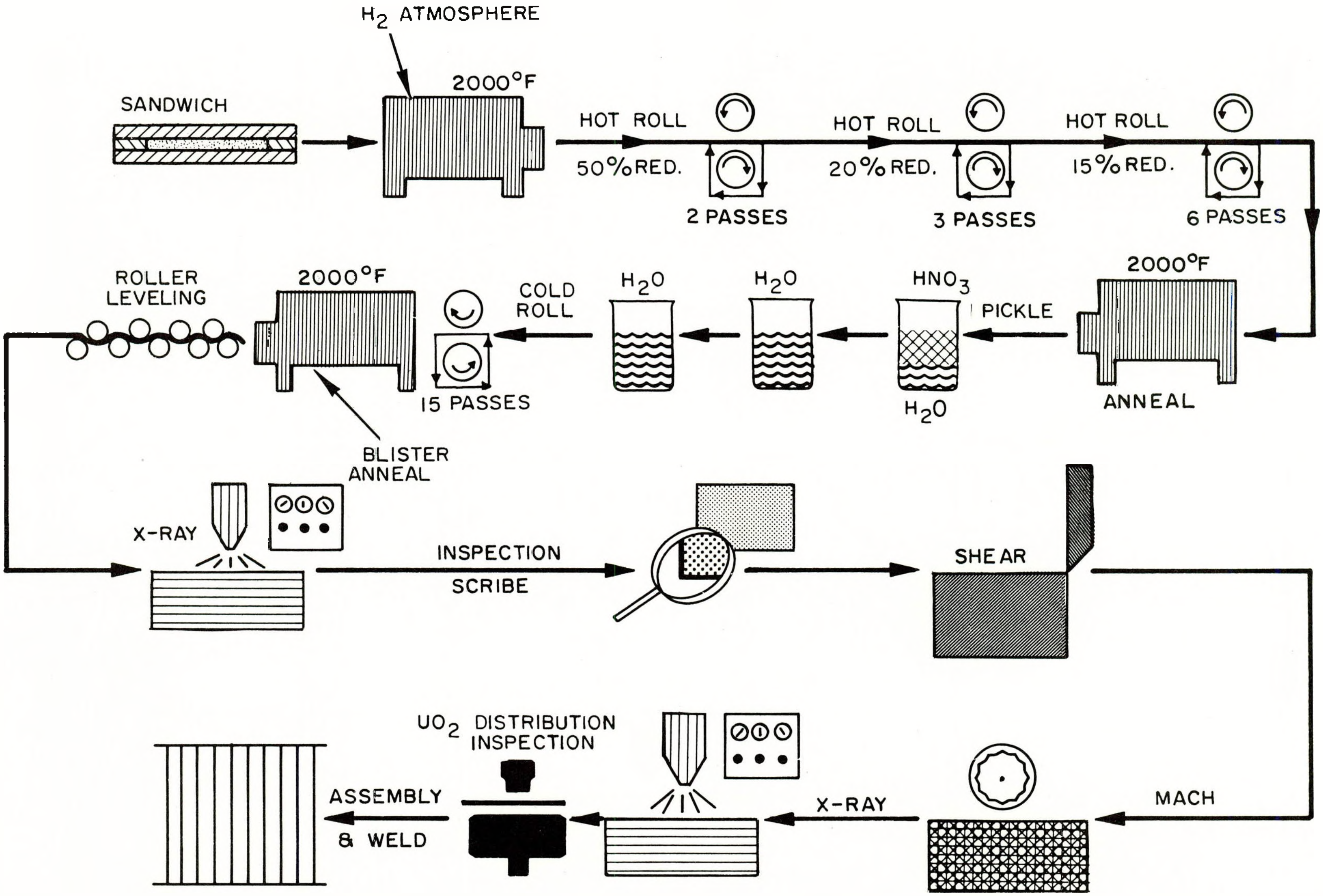


Fig. 7. OMRE Fuel Plate Fabrication Flowsheet

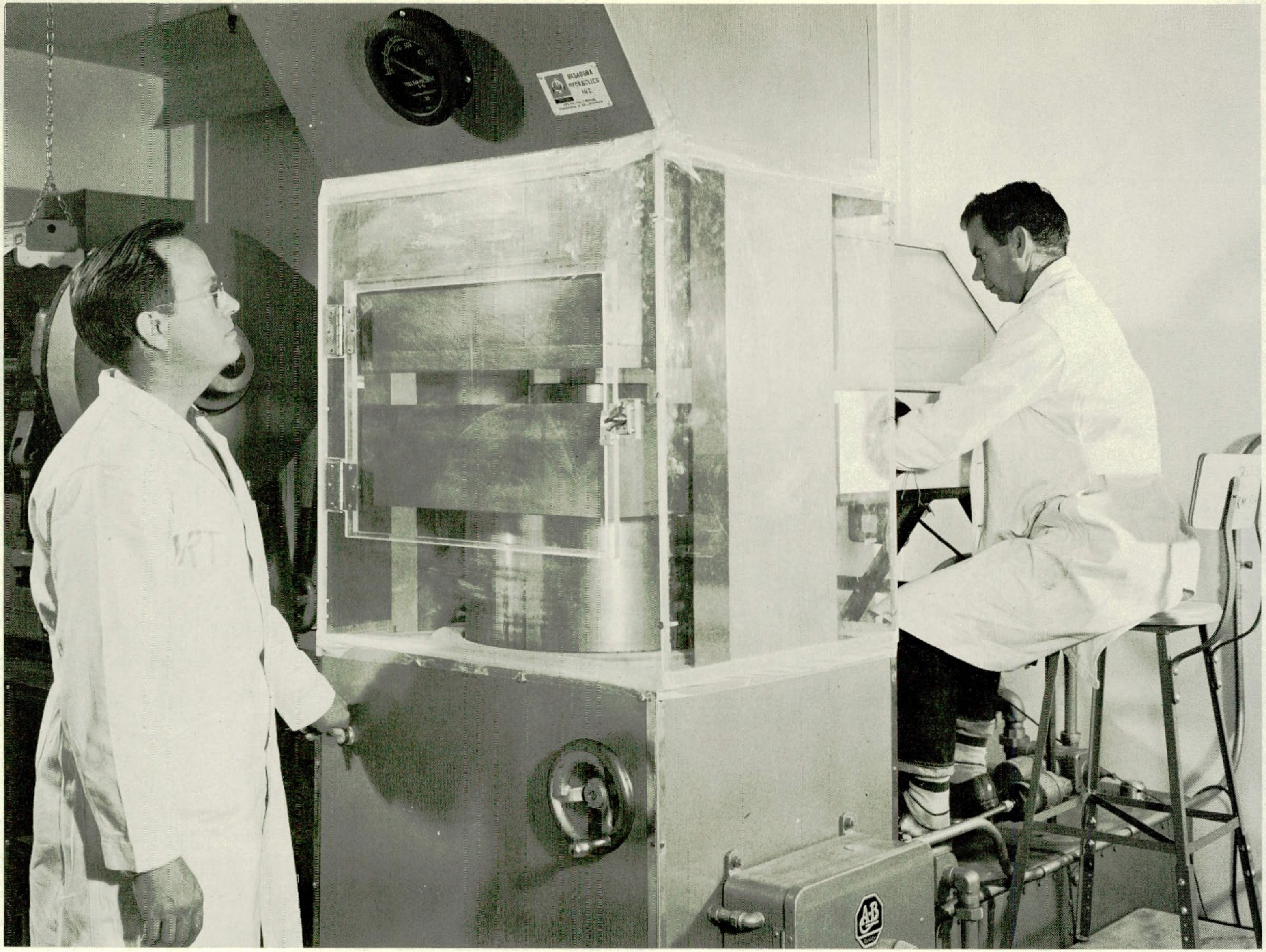


Fig. 8. Pressing Compacts for Fuel Core

with 30-mesh alundum prior to assembly of the sandwich. Figure 9 shows the components of the sandwich assembly before welding. Each cover plate was welded to the frame by heliarc, fusion welding. The vent hole was the only opening into the sandwich assembly. A water-cooled copper chill plate was clamped to each side of the assembly during welding to prevent oxidation of the inside surfaces.

C. HOT-ROLLING PROCESS

The sandwich was heated at 2000° F for 30 minutes in a dry hydrogen atmosphere. It was then hot rolled to a thickness of 36 to 38 mils on a 12-inch by 12-inch two-high rolling mill, as shown in Fig. 10. During the first hot-rolling pass, the sandwich was introduced into the rolls so that the end with the vent hole passed through the rolls last. This permitted the entrapped gases to escape and provided for closure of the hole as it passed through the rolls. During each of the subsequent passes, the sandwich was reversed, end for end, and turned over, face for face. The plate was reheated for each pass (at 2000° F). After the fourth pass, the plate was removed from the furnace and cooled, and 4-1/2 inches was sheared from the end that contained the exhaust hole and one inch was sheared from the other end to facilitate handling in subsequent passes.

After the last pass was completed, the plate was annealed for 15 minutes at 2000° F in hydrogen and cooled in air.

At the completion of the hot-rolling operation, the plate had elongated from its original 6-inch length to a length of 62 inches. The width increased from 4-1/2 inches to 5 inches.

During the hot-rolling operation an oxide coating, approximately three mils thick, was formed on each surface of the fuel plate; this had to be removed before the cold-rolling operation. The oxide was removed by pickling the plate for one hour at 160° F in the following solution:

Hydrofluoric acid	5 per cent by volume
Nitric acid	20 per cent by volume
Water	75 per cent by volume

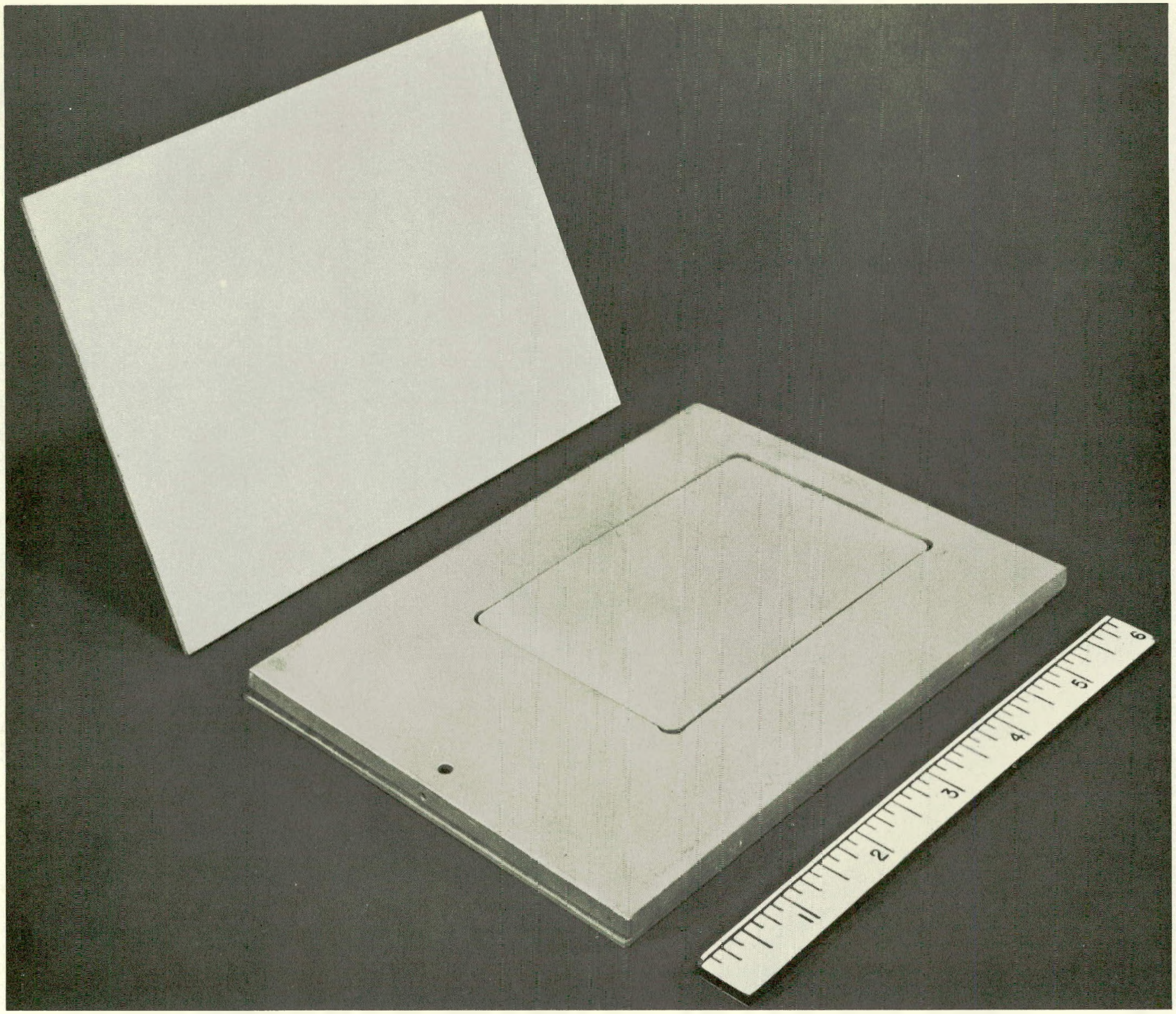


Fig. 9. Fuel Plate Sandwich Assembly Before Welding

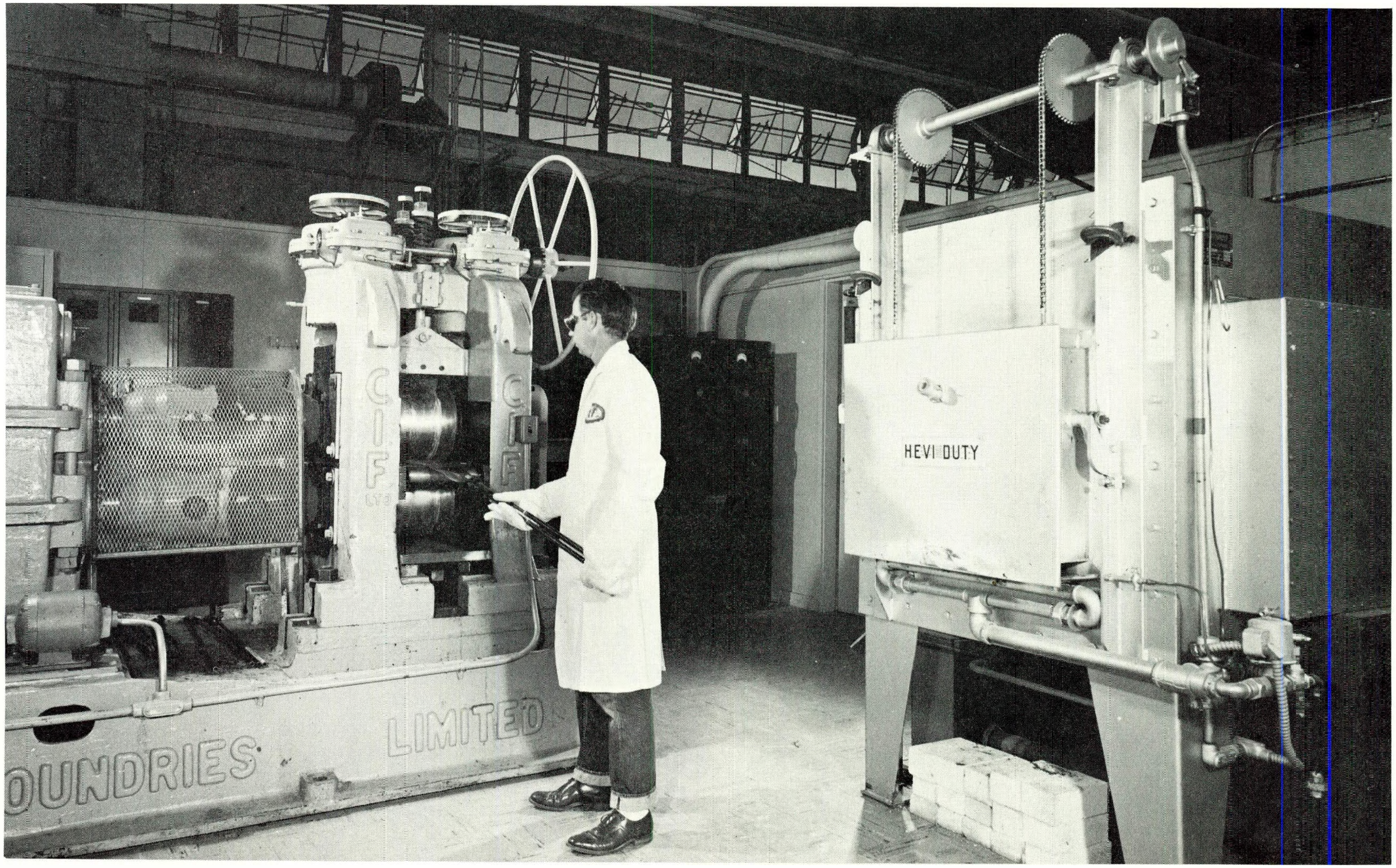


Fig. 10. Hot Rolling Plates for the Fuel Element Assembly

The plate, after pickling, was rinsed successively in three water baths and then air dried.

D. COLD-ROLLING PROCESS

The plate was cold rolled to a final dimension of 30 mils ± 0.001. The cold-rolling operation served not only to reduce the plate thickness to the required thickness and improve the surface finish but also to straighten any camber that might have been introduced during the hot-rolling steps. A very small reduction was made during each of the cold-rolling passes. Six to twelve passes were necessary to bring the plate to the final thickness.

E. BLISTER ANNEAL

The plates were heated for two hours at 2000° F in a dry hydrogen atmosphere to attain an annealed condition and to detect any unbonded areas.

Prior to annealing, the plate was coated on both sides with a suspension of MgO in water and then air dried. The MgO prevented plates from sticking to one another when a large batch of plates was annealed. The MgO coating was removed from the plates after the completion of the annealing cycle by washing in a 10 per cent solution of acetic acid in water, after which the plates were rinsed in clean water and then air dried.

The blister-anneal process annealed the cold-worked plates and caused a "blister" to form at any area where the cladding was not metallurgically bonded to the plate. If such a blister occurred within the area of the finished plate, the plate was rejected.

At the completion of the blister anneal, the plates were passed through a roller leveler (Fig. 11) for flattening. Several passes were sometimes necessary to produce a plate flat within 1/16-inch flatness.

F. CORE LOCATION

Two reference holes, one, 1/4 inch in diameter and the other, 5/16 inch in diameter, were punched through the plate frame along one side. (The section of the plate containing the holes was sheared off in a subsequent operation.) After the reference holes were punched, the plates were radiographed. Close contact

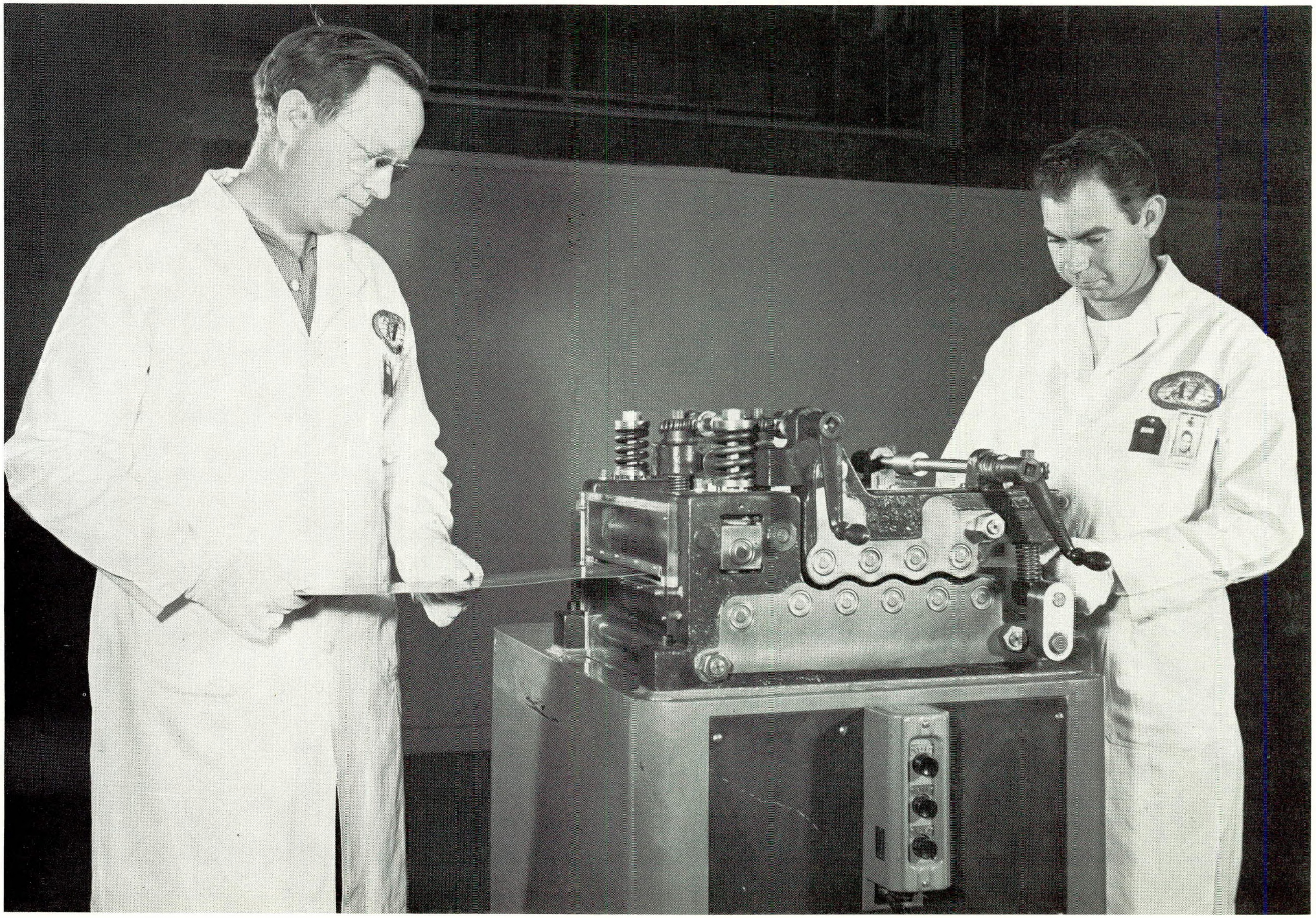


Fig. 11. Roller Leveling Fuel Plates

between the film and the plate was ensured by a clamping fixture. The film was exposed at 10 milliamperes at 150 kilovolts for 45 seconds at a distance of 60 inches from the source.

The fixture shown in Fig. 12, A was used for locating the core with respect to the scribed line that outlined the area of the finished plate. The developed radiograph was placed on the fixture as shown in Fig. 12, B. The radiograph was moved on the lighted screen of the fixture until the core on the radiograph was within the core layout lines on the screen. The radiograph was then taped in position to prevent movement. The fuel plate corresponding to the radiograph was placed over the taped radiograph.

The fuel plate was located so that the 1/4-inch and 5/16-inch reference holes of the plate coincided with the 1/4-inch and 5/16-inch images of the holes on the radiograph. The plate was then clamped to the fixture to prevent movement.

The template (Fig. 12, C) was placed on the fixture against the locating guides and clamped into position. The fuel plate was then scribed to shearing size, using the template as a guide.

The plates were sheared to the scribed lines. An accuracy of ± 10 mils was obtained on the sheared plates with the shearing fixture shown being used in Fig. 13.

G. MACHINING PLATES TO FINAL SIZE

The sides of the plain fuel plates were machined to final size by straddle milling, as shown in Fig. 14. A batch of 16 to 20 plates was stacked on a milling fixture which referenced the machining cut from one sheared edge. The entire batch of plates was then milled to size in one pass. The fixture was then removed to a vertical milling machine for machining of the slots on each end and on the side of the plate. The fixture was also used for machining batches of 18 to 20 tabbed plates on a vertical milling machine. After machining, the plates were radiographed again to ensure that the fuel cores were centered within the fuel plate.

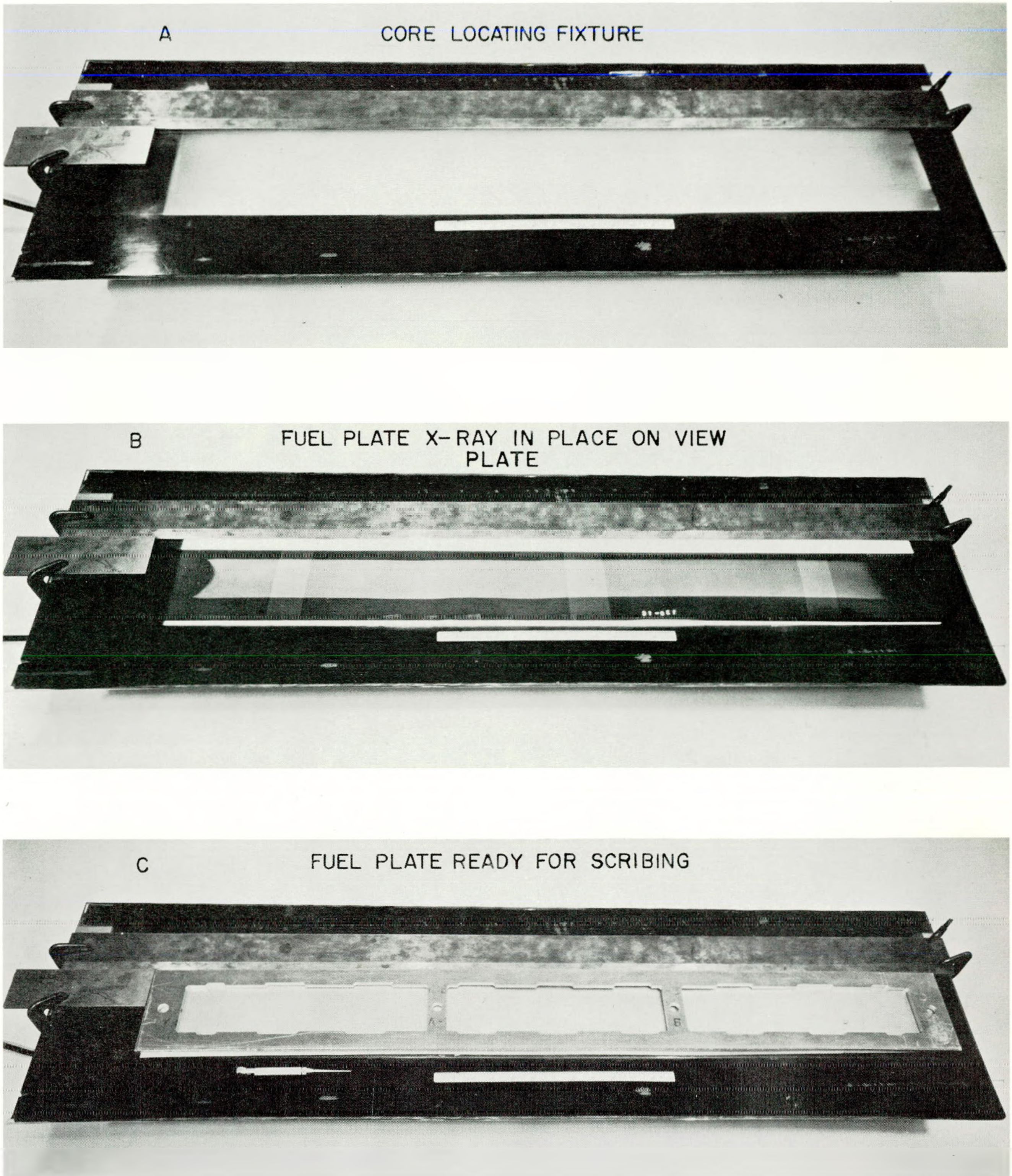


Fig. 12. Locating Core for Shearing Operation

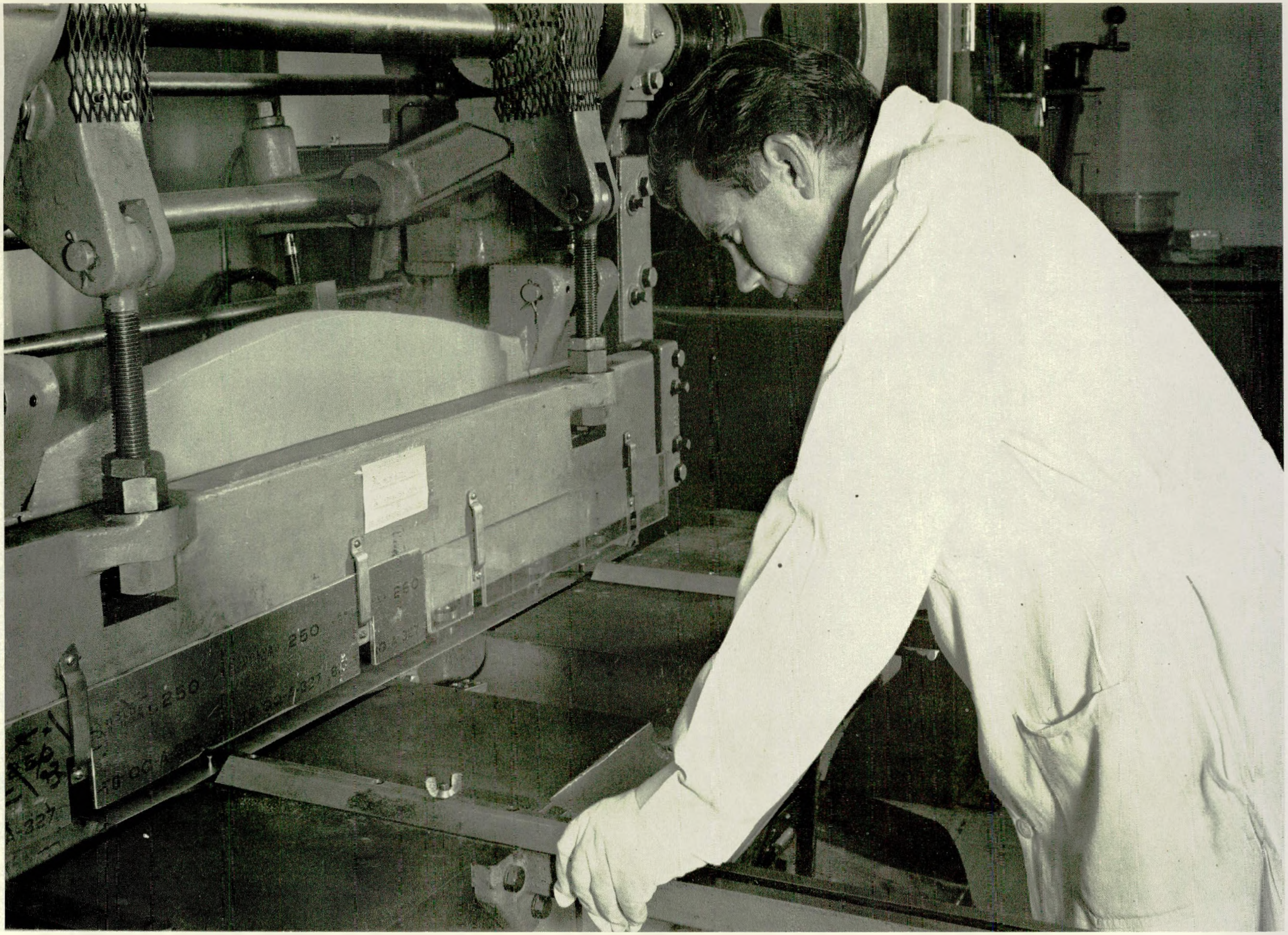


Fig. 13. Shearing Fuel Plate to Pre-Machining Size

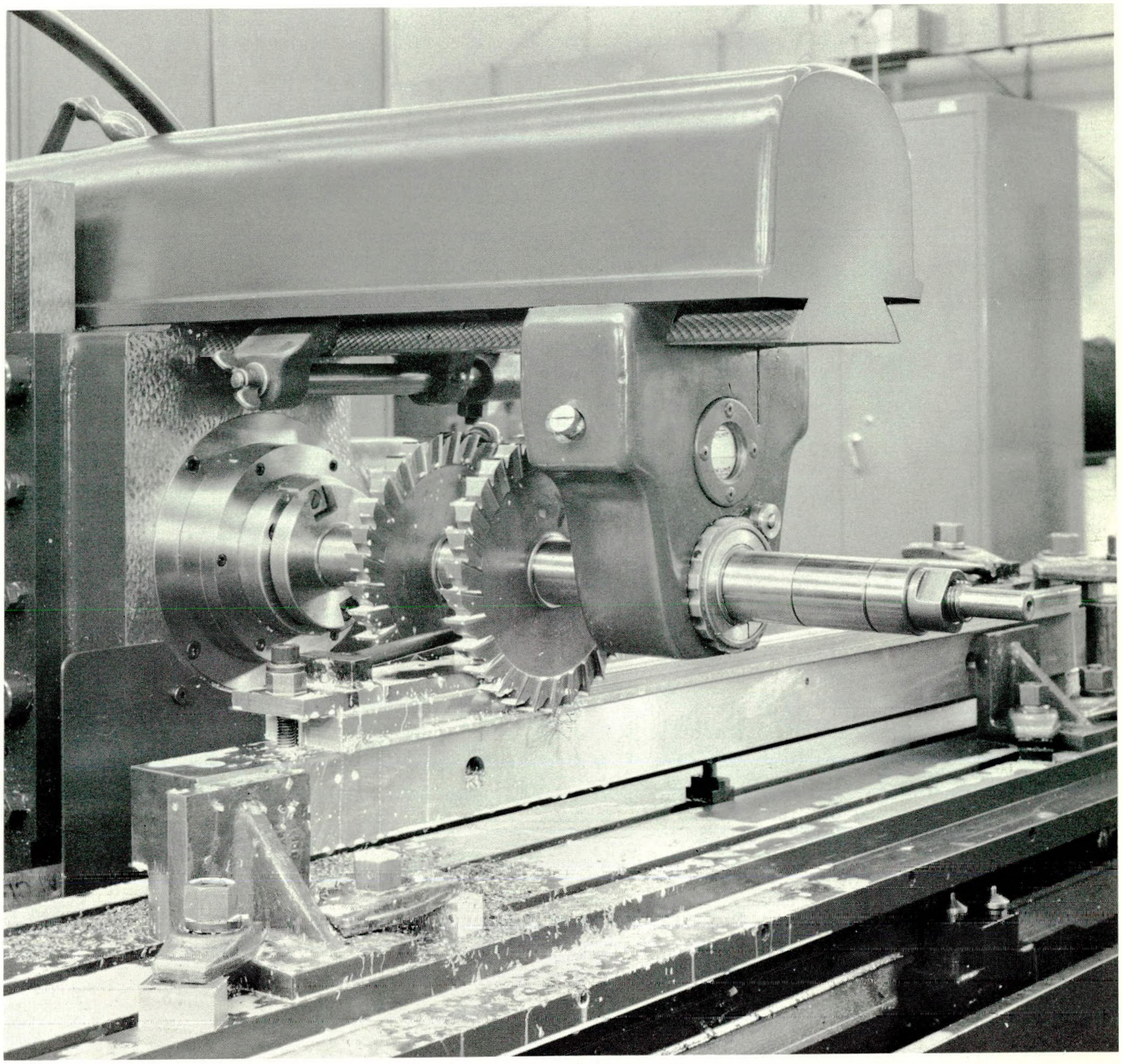


Fig. 14. Milling a Batch of 18 Fuel Plates to Final Size

H. UO_2 DISTRIBUTION INSPECTION

The UO_2 distribution of the machined plates was checked with a radiation gage, consisting of a radioactive source within a collimating head and associated electronic detecting equipment.

The plates were placed underneath the collimating head, and the UO_2 content of a 1/16-diameter spot was determined by the amount that the radiation was attenuated as it passed through the plate. Thirty such readings were made over the core of each plate. The readings were statistically analyzed to determine the UO_2 distribution of the plate.

I. FUEL BOX ASSEMBLY

The grooved side plates, the end plates, and the two tabbed fuel plates were placed into a tack-welding fixture. The plain, untabbed fuel plates were then slid into position along the grooves of the box as shown in Fig. 15. The retainer bar was inserted into the slots of the plates on the inlet end of the fuel box. The stainless-steel spacer pins were inserted into the slotted plates on each end of the fuel box. The fixture wing nuts were then tightened and the fuel box assembly was tack welded through the openings in the fixture as shown in Fig. 16. The tack-welded fuel box was removed from the fixture. The tabs projecting through the side plates were bent into position and the fuel box assembly was positioned on the weld stake for welding of the four corners of the box. Each longitudinal seam was made with the automatic welding head (shown in use in Fig. 17). No filler metal was added to the helium-shielded and helium-backed weld beads. The retainer bar and the spacer pins were manually heliarc plug-welded into place. The tool illustrated in Fig. 18 was used to check the spacing of the plates in the assembled fuel box.

The fuel box and the three end castings were aligned in the fuel-element-assembly positioning fixture for welding.

The four components were then manually welded with a helium-shielded, tungsten arc, as shown in Fig. 19. The fixture aligned the components and permitted the aligned components to be rotated for ease of welding.

All welds of the completed fuel element were inspected by the penetrant dye technique. The fuel element was inspected for alignment.

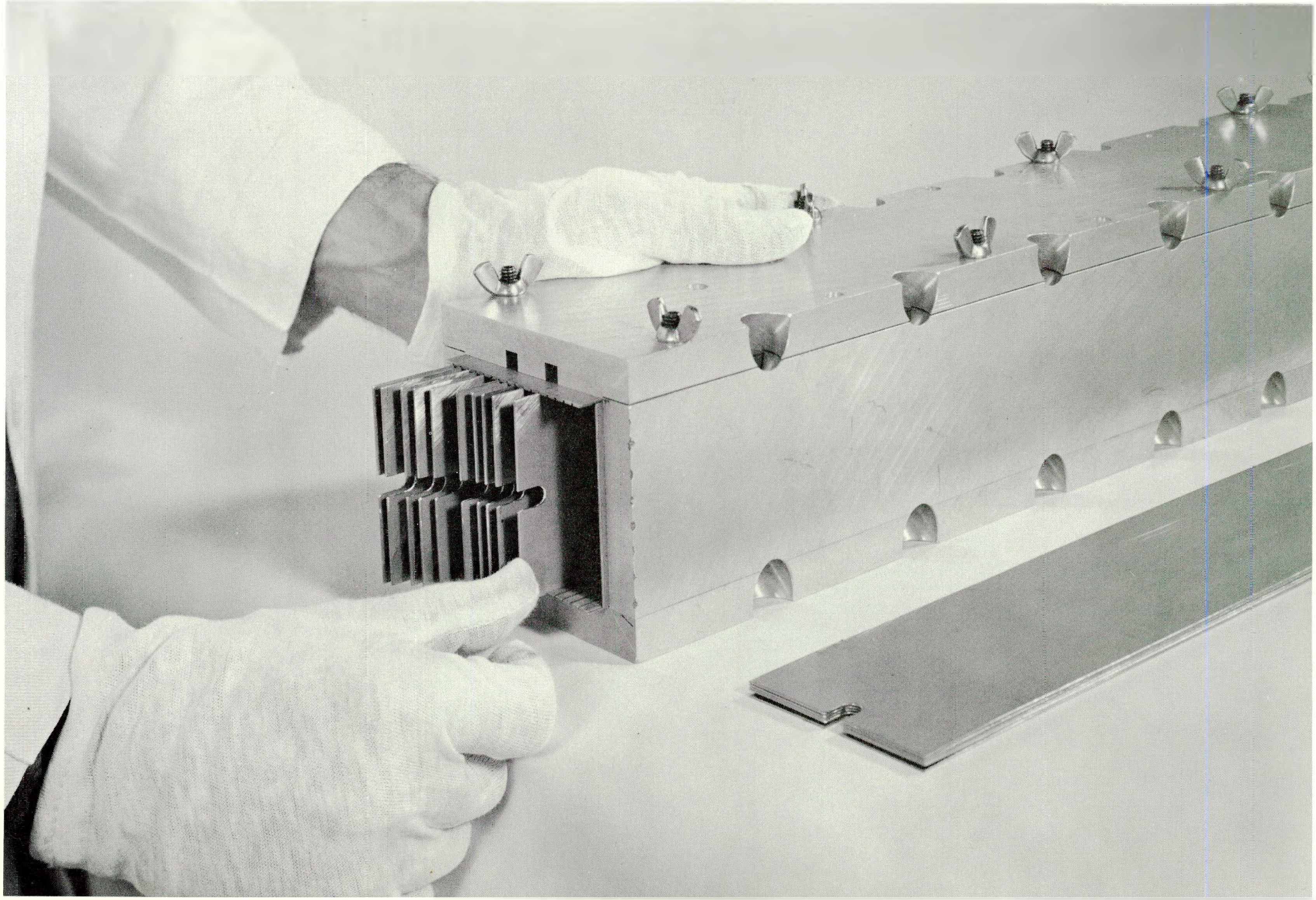


Fig. 15. Assembling Fuel Plates into Tack Welding Fixture

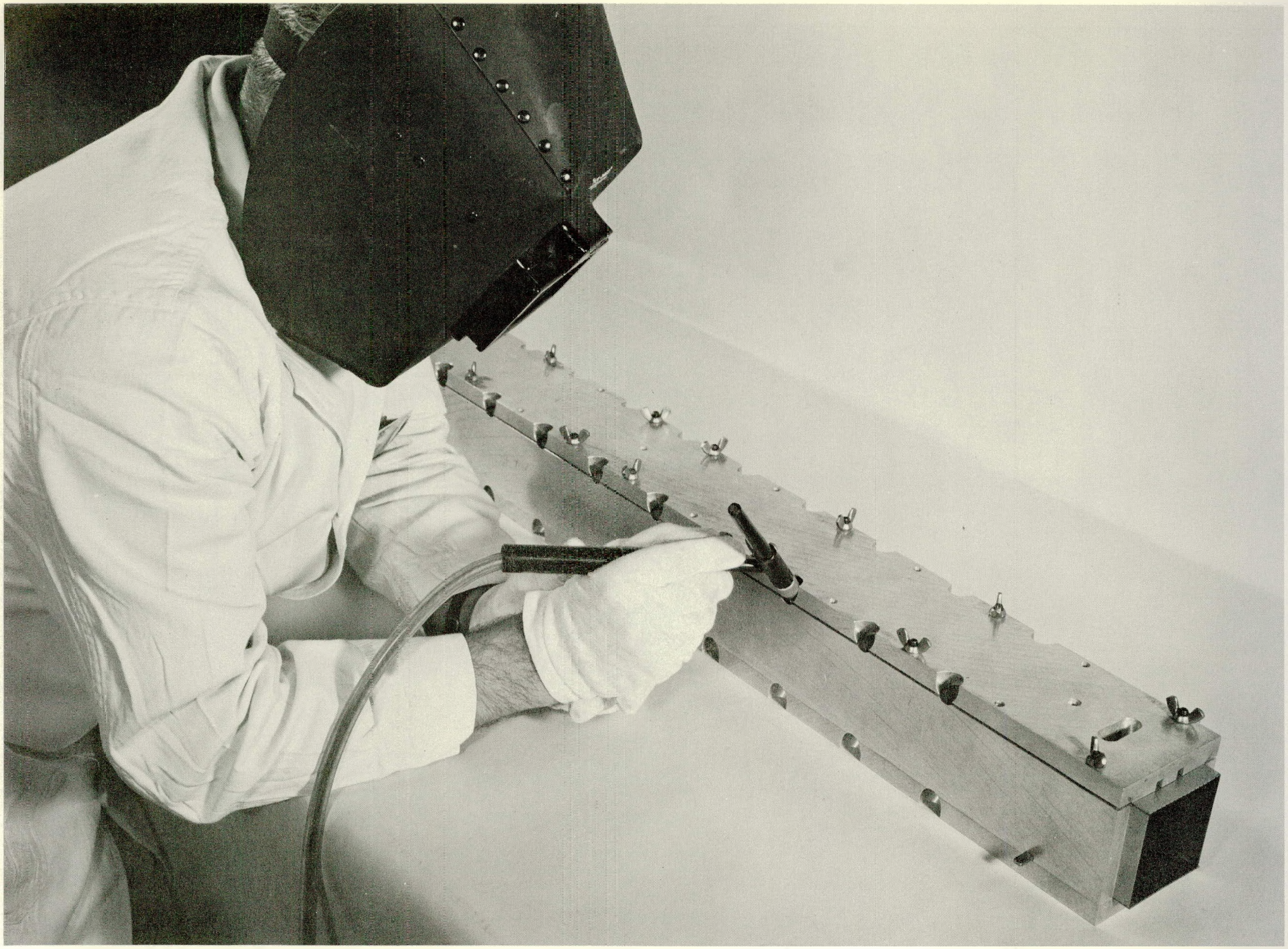


Fig. 16. Tack Welding Assembled Fuel Box in Fixture

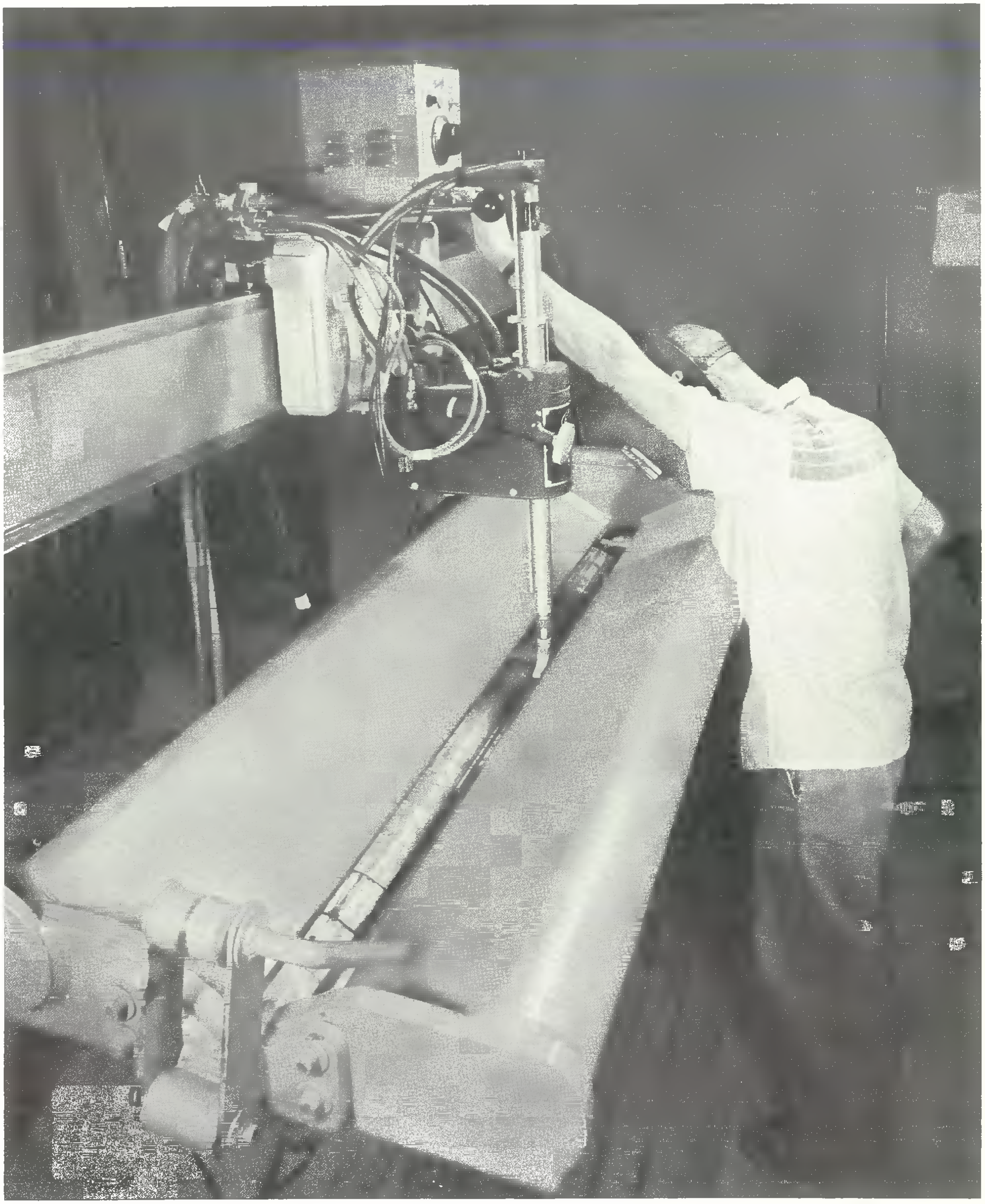


Fig. 17. Seam Welding Corners of Fuel Box on Welding Stake

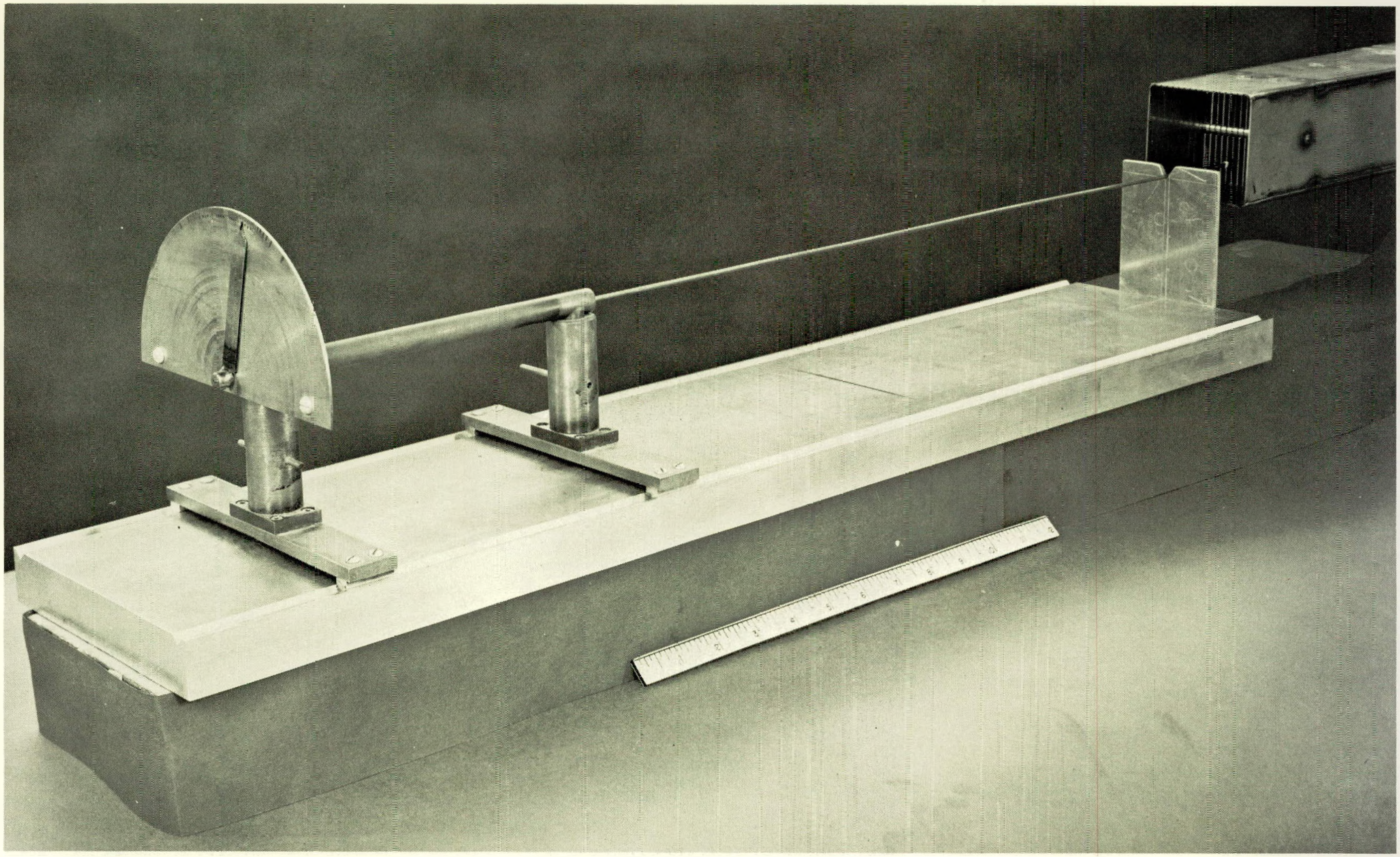


Fig. 18. Inspection Tool for Checking Spacing Between Fuel Plates

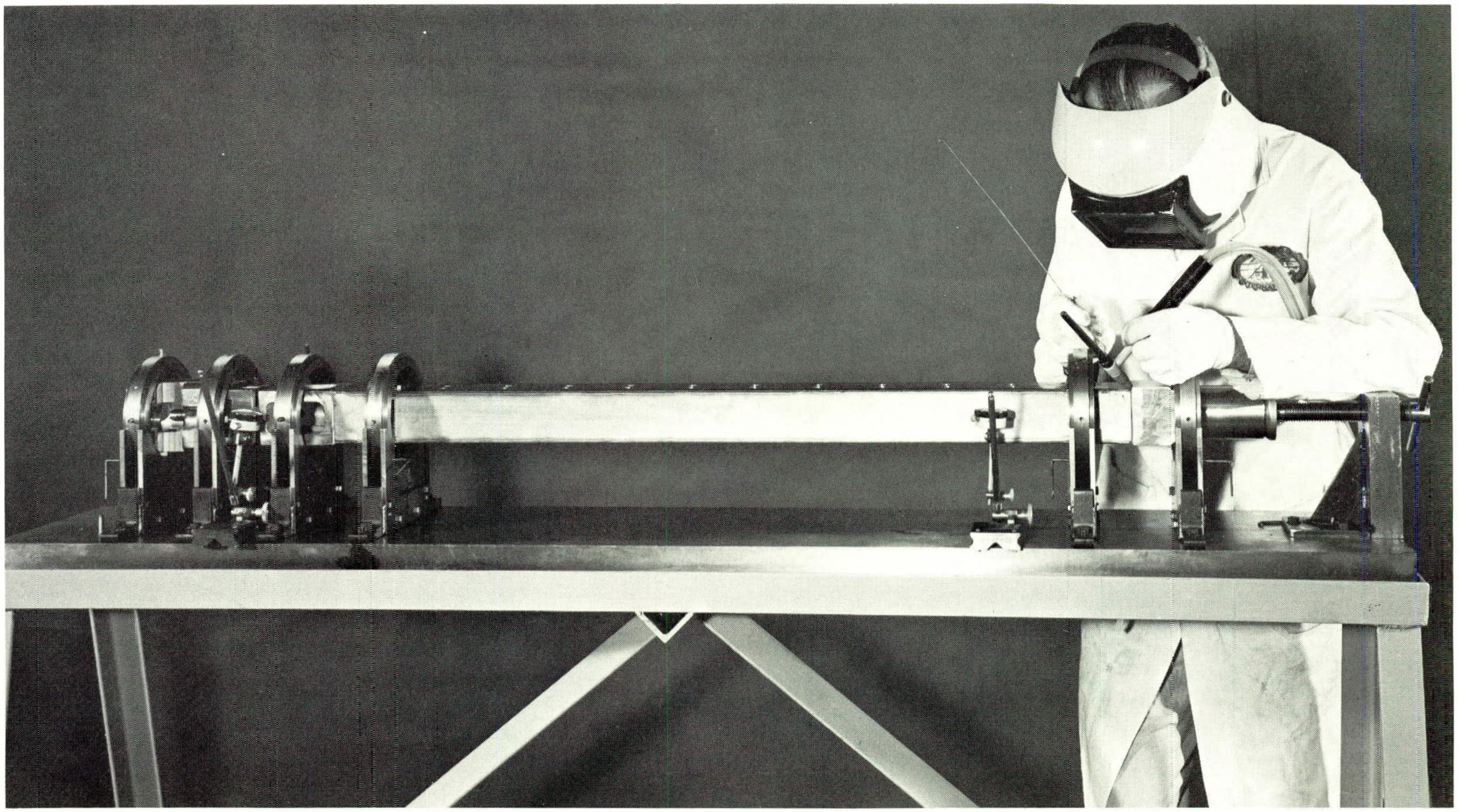


Fig. 19. Welding End Casting on Fuel Box in Alignment Fixture

The finished fuel element was degreased and then pickled in nitric acid-hydrofluoric acid solution.

V. FUEL ELEMENT ASSEMBLY ANALYSIS

The primary problem associated with the assembly of a fuel element for an organic-cooled reactor results from the large temperature differentials which are found between the active, uranium-containing components and the inactive components. The large temperature differentials are caused by the following factors, the first of which has not been encountered in previously used plate-type fuel elements:

1) Low heat-transfer coefficients of the polyphenyl moderator-coolant (with respect to water),

2) The temperature difference from one fuel plate to the next caused by differences in the neutron flux distribution,

3) A transverse temperature difference across each plate also caused by neutron flux changes,

4) The low thermal conductivity of stainless steel.

In previously used plate-type fuel elements, such as in the APPR-1, the problems associated with the last three items were also present, but were minimized by the use of a coolant with high heat-transfer properties (i. e., water).

A. FUEL ELEMENT STRUCTURAL PROBLEMS

Two structural problems which arise from the large temperature differentials in a polyphenyl-cooled, stainless-steel fuel element are transverse and longitudinal bowing of the fuel plates. A combined analytical and development program resulted in the evolution of the "floating-plate-type" fuel element, which should be adequate to handle the stresses that are anticipated.

A preliminary analysis showed that the temperature of the outer stainless-steel box containing the fuel plates would be approximately 200° F less than the average temperature of the hottest fuel plate.

A temperature differential of such a magnitude would cause the fuel plates of a bonded assembly to buckle transversely. If the temperature of the outside or end plates of the box enclosing the plates could be increased, the transverse buckling problem would be minimized. A decision was made to introduce some fuel to the end plates to increase their temperature. By calculation, a 13 per cent UO_2 content would cause the temperature of the outside plate to approach the temperature of the second and hottest plate. This equalization of temperature would minimize transverse plate distortion. It was found, however, that fuel in the outer or end plates of the fuel element was not necessary with the floating-plate-type assembly.

A longitudinal buckling problem became apparent when the analysis indicated that the difference between the average fuel plate temperature and the peak temperature of the hottest plate was 60° **F**. The longitudinal and transverse plate buckling aggravated the problem of transferring the heat from the fuel element to the coolant by varying the coolant flow passages.

B. WELDING ANALYSIS

During the initial assembly development work, the welding program (which is fully described in Section IV-B) resulted in a fuel element that was assembled by transverse welds which were used to hold the fuel plates in place. A preliminary numerical analysis indicated that the proposed weld bead arrangement would be unsatisfactory due to the large shearing forces on the welds. Attempts were made to strengthen the structure by additional weld beads, but the final analysis showed that only a fully-welded box with each fuel plate held in place by full-length longitudinal weld beads would be satisfactory for use in the polyphenyl coolant-moderator. Such a fuel box was impractical to produce by welding techniques due to the distortion caused by weld metal shrinkage during fabrication of the box.

C. BRAZING ANALYSIS

Assembly by brazing techniques was also investigated (see Section IV-B). A brazed fuel box assembly was developed that was distortion-free, as fabricated. Each fuel plate was firmly held in its groove by a copper braze. With 16 active fuel-loaded plates and two inactive end plates, an analysis showed that buckling of the fuel plates was still possible. The decision to add fuel to the two end plates to equalize temperature differences would alleviate the buckling problem, but doubt still remained concerning the operational and structural behavior of the element. The brazing of elements containing fuel plates with attached thermocouples would have been very difficult. Of the 36 elements that were to be fabricated for the reactor, 14 elements contained five thermocouples each. (The thermocouple attachment is discussed in Section VIII.)

D. STRUCTURAL TESTS

A number of tests were made to confirm the numerical analysis of the brazed fuel element and to study the structural behavior of the materials involved.

Fatigue tests of actual fuel plates loaded with depleted UO_2 were made. Results of the fatigue tests showed that strains equivalent to an elastic stress of 200,000 psi could be sustained for 4000 reversed cycles. Bending tests on grooved side plates taken normal to the grooves showed that the plate behaved as a plate of a thickness equivalent to the depth between the smooth face of the plate and the bottom of the groove (0.020 in.). The plate acted as a full-thickness plate (0.050 in.) when bending tests were performed on segments taken parallel to the grooves.

Refined heat-transfer calculations showed a difference of 145° F between the average fuel element temperature and the peak temperature on the hottest plate. Stress analysis on this plate, considering the above temperature difference, indicated an inelastic buckling condition which could only be investigated experimentally.

At this time, the "floating plate" design (described in Section II) was proposed to eliminate the problem of fuel plate buckling.

E. PLATE DEFORMATION TEST

To demonstrate the existence of, or lack of plate buckling that was anticipated from the brazed-type and "floating plate-type" assemblies, respectively, a test mock-up was constructed in which the temperature profile expected in the reactor could be duplicated on a fuel plate.

The test apparatus consisted of a 12-inch-long box containing only the fuel plate to be measured. One of the end plates of the fuel box was drilled to permit measurements of the deflection of the fuel plate being tested. Calrod heaters were positioned on both sides of the test plate on the line where the peak of the temperature profile of the plate occurs. To obtain the required temperature distribution across the plate, water was sprayed on the outside of the fuel box and air was blown down through the inside of the box along the center of the test plate. Temperature data was obtained from thermocouples attached to the test and grooved side plates. The test plates were temperature-cycled until a stable condition had been reached.

Figure 20 summarizes the results of the tests. A maximum deflection of 0.064 inch was obtained with a brazed plate and 0.010 inch with a floating tabbed plate. Inspection of the brazed plate showed a permanent deformation of 0.032 inch. The floating plate showed no measurable permanent deformation and no evidence of internal stresses. These tests indicated that the floating plate fuel element was more desirable for an organic coolant-moderator than the brazed assembly; however, it was still necessary to determine the magnitude of the load on the pin supporting the end of the floating plate.

F. LOAD ON SUPPORT PIN

It was found that the support pin would have to carry a 50-pound load in order to overcome the static-friction between the fuel plate and the grooved side plate. (The 50-pound value is for a full-length fuel plate.) Accordingly, a retainer bar welded to the grooved side plate was added to one end of the fuel plate to minimize the load on the support pin and to restrict longitudinal plate growth to one direction.

G. VIBRATION TEST

Due to high-velocity coolant flow, there is a possibility that the free floating plates will vibrate. This vibration could dislodge or even cause structural failure of fuel plates. The vibration can be caused by differences in pressure on the two sides of a fuel plate due to local turbulence. If the frequency of periodic disturbances caused by turbulence is approximately the natural frequency of the fuel plates, resonant vibrations having large, destructive amplitudes may be induced in the plates.

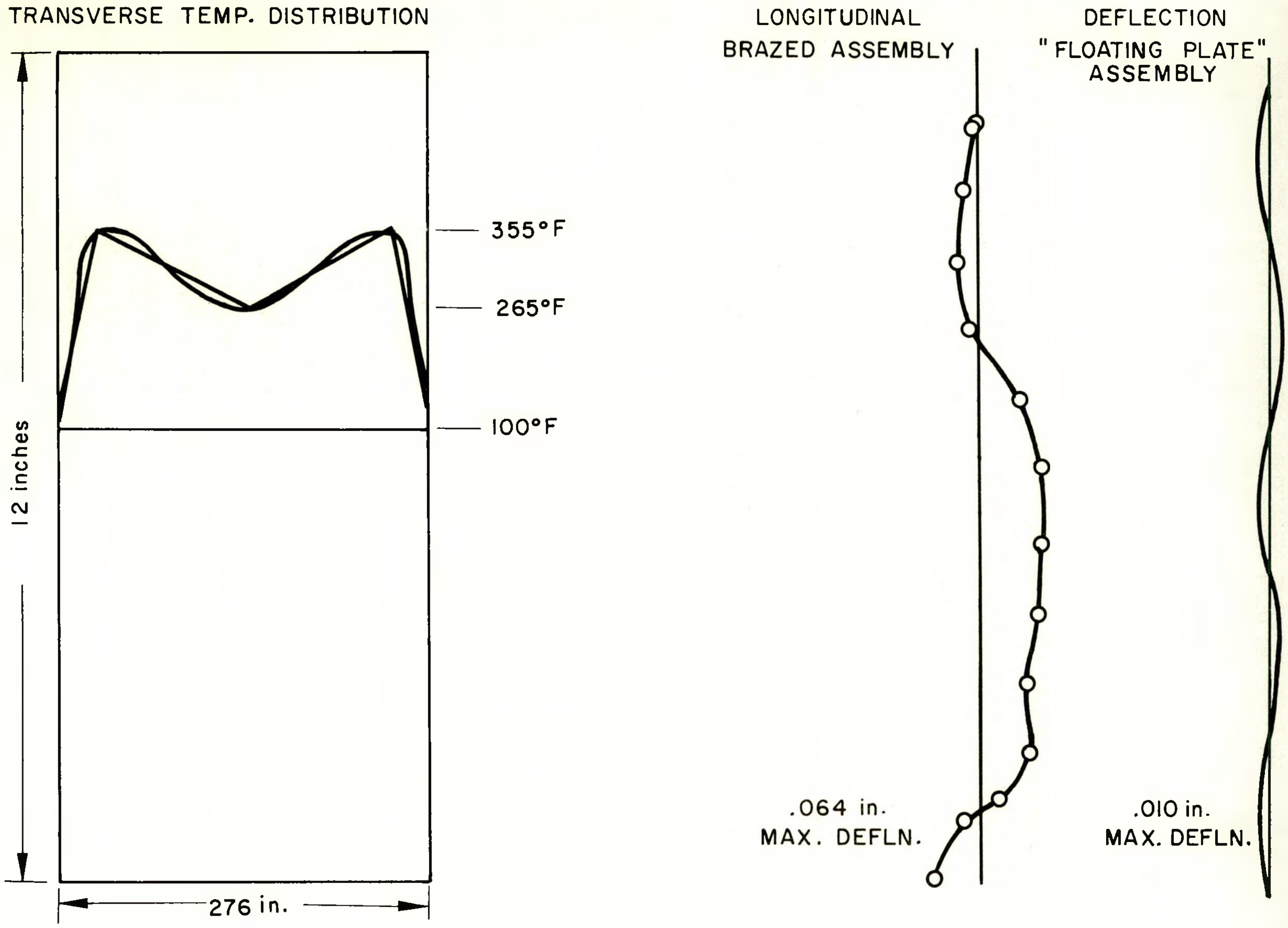


Fig. 20. Comparison of Plate Deformation Due to Thermal Stresses of Brazed and Floating Plate Assemblies

An analysis of the fuel element indicated that a resonant condition may be expected at coolant flow rates of four feet per second and 16 feet feet per second. To determine the magnitude of such vibrations under reactor operating conditions, the following test was performed.

A test assembly was constructed to simulate the structural stability of the OMRE fuel element and to permit visual observation and vibration measurements to be made. The assembly was mounted in a hydraulic loop in which reactor coolant flow conditions could be duplicated. The assembly consisted of a plastic fuel box which contained simulated fuel plates of stainless steel. Vibration amplitudes were obtained with strain gage pick-ups mounted on the fuel plates.

Test Results:

1) Oscillograph recordings of the strain gage vibration pick-ups were obtained over a range of water velocities that bracketed the OMRE coolant flow velocities. The recordings indicated the maximum amplitude of vibration of the fuel plates was less than one mil and occurred at the maximum flow velocity of 15 feet per second.

2) Visual observation of the fuel element mock-up during operation showed no perceptible movement of the fuel plates.

3) No wear was apparent in the grooves of the plastic side plates after the completion of the test.

It was concluded that vibration of the OMRE fuel element assembly under design coolant flow conditions will not be a problem in reactor operation.

H. TAB PULL-OUT TEST

Tests were made to determine the load the bent tabs would support before they would be pulled out of the slots of the side plates. Several different widths of tabs and several different slit configurations of the tabs were tested. The slitting enabled part of the tab to be bent in either direction. It consisted of a 1/4-inch tab that was slit in half before the tabbed plate was assembled into the fuel box. In actual practice, the tabs will be required to support approximately 15 pounds. The tests showed that they will support 150 pounds. It should also be pointed out that the actual fuel box configuration will be stronger than the test configuration, due, primarily, to the restraining effect of adjacent tabs and the welded box.

I. LEAK TEST

The 52 slots in the fuel box through which the tabs protruded were made sufficiently long to allow the plates to move longitudinally as required by thermal expansion. A leak test under reactor operating conditions was made to determine the magnitude of coolant leakage through the slots. The test indicated that only about four-tenths of one per cent of the flow through the fuel element would be lost through the elongated holes provided for the tabs.

J. PRESSURE CYCLING TEST

Under reactor operation conditions, a coolant pressure drop of about seven pounds per square inch is expected. A pressure cycling test that simulated the seven-pound range was made on a 12-inch model of the "floating" plate fuel element. Since air was used to pressure cycle the mock-up, the slots were plugged with soft solder to prevent leakage. The solder was in a plastic state at the conditions of the test. The mock-up was cycled at 500° F at a frequency of 30 cycles per minute for 1000 cycles. The test results were very favorable. The maximum permanent deformation was five mils for the grooved side plates and 13 mils for the two outside end plates.

VI. FUEL ELEMENT FABRICATION DEVELOPMENT

A. FUEL PLATE DEVELOPMENT PROBLEMS

A development effort was necessary in almost all of the steps that were used to fabricate the fuel plates, such as the compact preparation, hot rolling, and machining steps. The main problems that occurred during the fabrication development program were as follows:

1) Lack of bonding of the cladding to the core and picture frame.

2) Excessive oxidation of the plate surface during the hot-rolling operation.

3) Surface defects occurring during the hot-rolling operation.

4) Accurate location of the core for machining the fuel plates to final size.

The development of solutions to the above problems is discussed along with the development of some of the other fabrication techniques.

1. Fuel Core Compact Development

The stainless steel-UO_2 compact was made by conventional powder metallurgy practices. The powders were blended, placed in a die, pressed, and sintered. The development program involved the establishment of parameters for the following items:

a) The die configuration

b) Compact size

c) Powder blending techniques

d) Die pressing pressures

e) Conditions of the sintering operation.

The compacts for the development program were made from stainless steel and depleted UO_2. The particle size and shape, and the distribution of the depleted material were essentially the same as for the enriched UO_2 that was used in the production program.

Initially, a die for producing a rectangular compact with square corners was chosen. A single-action, single-cavity die was constructed. The die, shown being loaded with powder in Fig. 21, consisted of three parts: the die body containing the cavity, a bottom punch which was stationary during the pressing operation, and a movable upper punch. The powder was pressed between the upper and lower punches and ejected by forcing the punches and compact through the bottom of the die. Test compacts that were made with the square-cornered die indicated that considerable difficulty would be encountered in keeping the square corners intact during ejection and subsequent handling of the compact. A die with rounded corners of a 1/4-inch radius alleviated the problem.

A pressure of 49 tons per square inch was found to be necessary to produce a green compact that could be safely handled without breakage and with a density that would prevent edge-cracking during hot rolling. The resultant compact had a density of approximately 80 per cent of the theoretical density.

Difficulty was also experienced in preventing the ejected green compact from laminating when it was ejected from the die. Different die lubricants and changes in the rate of pressure did not appreciably decrease the occurrence of

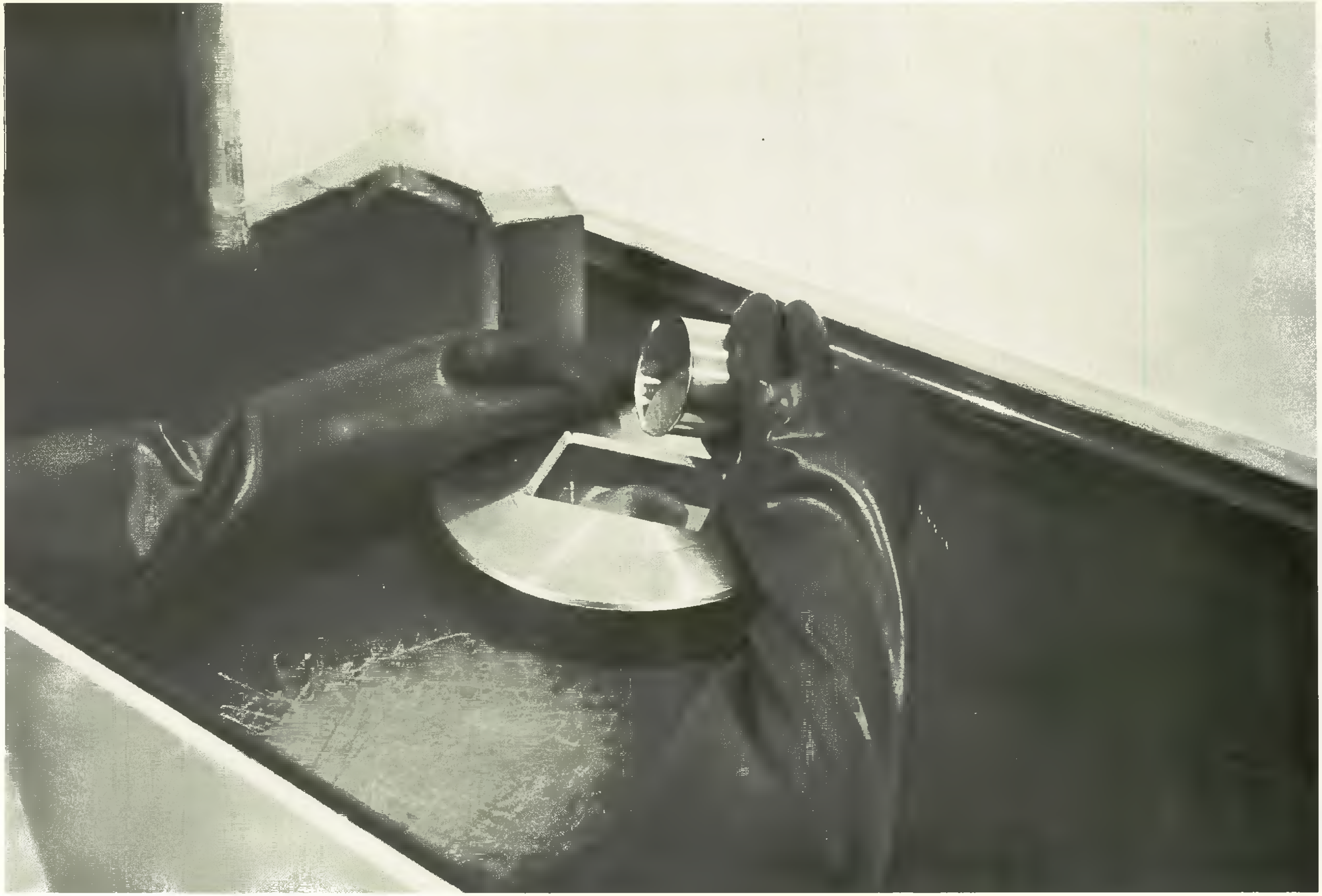


Fig. 21. Pouring Powdered Fuel Ingredients into Die Prior to Pressing Compact

the lamination. However, a 0.005-inch by 1/4-inch relief taper ground on the ejection side of the die decreased the laminations. Occasionally, though, a compact containing laminations was produced. The use of rubber blocks to provide a back pressure on the compact while it was being ejected eliminated any further laminations.

The size of the finished rolled core was required to be 2.50 inches wide by 0.020 inches thick by 36 inches long. Although the approximate size of the starting compact was calculated, the actual size had to be empirically determined. Compact density, UO_2 to stainless-steel ratio, picture frame opening size, and hot-rolling temperatures were some of the factors that influenced the final size of the core. The experimentally-determined size of the pressed compact was 2.4 inches by 3.9 inches.

In order to obtain a fuel plate with a predictable heat flux, the UO_2 must be uniformly distributed throughout the core. A primary factor that affected the final distribution of the UO_2 in the core of the OMRE fuel plate was the blending of the UO_2 and stainless-steel powders.

After a survey of the available small-capacity dry blendors, a Patterson-Kelly Twin Shell unit was chosen. The blending is achieved by tumbling the powders inside a unit that consists of two cylinders arranged in a 90 degree "V." The apex of the "V" splits the powder charge and recombines the two parts once each rotation. It was determined experimentally that a blending time of one hour provided uniform mixing. The efficiency of the blending action was checked by chemically analyzing samples taken from the batch of powder. Difficulty was experienced in obtaining representative samples from the batch. Consequently, after the first feasibility run of the process, it was decided to blend each die charge for each compact separately as a means of ensuring that the correct weight of U^{235} was placed in each fuel plate. However, further studies that were made of the UO_2 distribution of the finished plates indicated that the batch blending system (where all of the UO_2 and stainless-steel powder for all of the plates for one fuel element were blended together) produced a more uniform UO_2 distribution than the individual compact blending system (where the stainless steel and UO_2 for one compact were blended together). The UO_2 distribution studies are fully discussed in Section II. The batch blending technique was used for the majority of the production batches.

The pressed green compacts were sintered in sealed retorts in a dry hydrogen atmosphere for 1-1/2 hours at 2150° F. Tests showed that it was necessary to purge air from the retort with dry argon or other inert gases and then introduce the hydrogen at ambient temperatures before the retort could be placed in the furnace. A reverse procedure was used when the retort was removed from the furnace. The hydrogen was allowed to flow until the retort had cooled to below 300° F. For safety reasons, the hydrogen was then purged from the retort with argon before opening the retort. The above procedure minimized the chance of oxidation of the compact.

2. Hot-Rolling Technique

The sintered compact was placed in a sandwich assembly (Fig. 9) for the cladding operation. This assembly consists of a 4-inch by 6-inch by 1/4-inch-thick picture frame which contained a machined opening for the compact. Sufficient clearance (0.020 inch) was provided between the compact sides and the frame opening to permit the compact to be dropped in the opening without scraping and possibly losing accountable material. A cover plate was welded to each side of the picture frame to form the sandwich. The sandwich was then hot rolled to a 37-mil thickness.

a. Cladding-to-Core Thickness Ratio

In the finished fuel plate, a cladding-to-core thickness ratio of one-to-four is required (i. e., 0.005-inch cladding to 0.020-inch core). The same ratio was found to be satisfactory for the sandwich assembly, 1/16-inch-thick cover plates and a 1/4-inch-thick core.

b. Component Cleaning

To facilitate bonding during the hot-rolling operation, all of the sandwich components had to be clean. The compact was handled with clean, cotton gloves to preserve its clean surface. The other components, made from mill-stock stainless steel, contained an oxide film and were covered with oil and dirt from machining and handling.

The components for the first developmental sandwiches were cleaned by degreasing and pickling. Since the pickling process was somewhat cumbersome, wire brushing and sand blasting were investigated. Sand-blasting the component surfaces with 30-mesh alundum proved to be the most practical method. After sandblasting, the surfaces were brushed to remove the grit and then washed in a 90 per cent isopropyl alcohol solution.

c. Cladding-to-Core Bonding

Initially, the sandwich covers were spot welded to the frame. However, it was difficult to maintain a furnace atmosphere dry enough to prevent oxidation of the surfaces that were to be bonded. To minimize the possibility of the furnace atmosphere from entering the sandwich and causing subsequent blistering, the covers were heliarc seam welded to the frame. The weld bead was continuous except for a 1/4-inch section on the end of sandwich through which the gases inside the sandwich could exhaust. Considerable improvement was noted, although the frequency of blister occurrences was still too great. Welded sandwich assemblies that were dismantled showed the formation of an oxide film on the inside surfaces around the periphery of the sandwich, adjacent to the weld. The oxide film formed during welding was eliminated through the use of water-cooled copper chill blocks. The chill blocks were clamped to each side of the sandwich to prevent overheating of the metal surfaces adjacent to the weld.

Some doubt existed as to whether the blisters were the result of poor cleaning of the components or of oxidation of the interior surfaces of the sandwich assembly during hot rolling.

A number of sandwiches were prepared to determine the cause of the blistering. One group of samples was prepared in the normal manner and the other group was evacuated before hot rolling. The second group was heated at 300° F for four hours during the evacuation cycle to drive off as much gas as possible. Both groups were hot rolled under identical conditions.

Blisters occurred on about 75 per cent of the group prepared in the normal manner, and no blisters occurred on the plates that had been evacuated. The tests indicated that the cleaning had been adequate and that the blisters were caused by atmospheric conditions, either in the gas that was present in the sandwich or in the furnace atmosphere.

Although the evacuation technique was capable of producing blister-free fuel plates, the method was very cumbersome for plate fabrication in production quantities.

To decrease the chance that a blister could reach the fuel plate area, the opening in the frame for the compact was moved away from the exhaust opening by offsetting it as shown in Fig. 9. Although the chance of a blister reaching the fuel area was decreased, it was considered desirable to eliminate all blisters.

A test was made with the following variables to determine a practical method of eliminating the blister problem:

1) As a control, a group of sandwiches was made by the technique of evacuating before hot rolling.

2) The cover plates of the next three groups were drilled at the end with 1/32-inch, 1/16-inch, and 1/8-inch holes, respectively, to determine the effect of the exhaust-hole sizes.

3) Another group contained exhaust holes that were drilled in the end of each cover plate and a small stainless-steel flap that was welded over the opening in such a manner that the hole was sealed when the sandwich was passed through the rolling mill during the first pass. The cover over the hole also inhibited the exchange of gases between the sandwich and the furnace atmosphere.

4) The next group contained an exhaust port formed by two holes, intersecting in a "T," that were drilled in the end of the picture frame. The holes allowed the gases on each side of the sandwich to escape through the end of the picture frame as it passed through the hot rolls. The opening was sealed by the first hot pass through the rolling mill.

All of the sandwich assemblies were hot rolled under identical conditions. No blisters were developed on the plates in the control group that were made from sandwich assemblies which were evacuated before hot rolling. The second group with the different-sized exhaust holes indicated that there was less chance of blistering with smaller exhaust holes. No blisters occurred in the third and fourth groups. Since the "T-hole" technique that was used in the fourth group was better suited for production than the "flap-sealing" technique, it was adopted for plate fabrication.

d. Surface Defects

Occasionally, a number of fuel plates were rejected due to small depressions in their cladding. These surface defects occurred during the hot-rolling process. Examination of the defects disclosed that they were caused by foreign particles that were picked up from the furnace and subsequently rolled into the surface of the plate. Metallographic examination of the defects, an example of which is shown in Fig. 22, indicated that the cladding was not perforated or appreciably reduced in thickness. However, since there was no assurance that the cladding was within specifications, all plates with similar surface defects were rejected. The occurrence of surface defects was minimized by covering the furnace hearth plate with a clean, stainless-steel plate before each batch of fuel plates was hot rolled.

e. Core Formations

Due to the nature of the rolling process, the edge of the fuel core was not square.* Figure 23 shows two cross sections of the core edge which illustrate the "cupping" or "finning" that occurs during the rolling process. These phenomena were minimized by selecting a proper rolling schedule. This condition, of course, does not affect the over-all performance of the fuel plate.

3. Cold Rolling

The cold-rolling operation reduced the hot-rolled plate to the required thickness and improved the surface finish of the plate. Steps were also taken during the cold-rolling cycle to straighten any camber or bow that might have been introduced during the hot-rolling steps. Unless the core of the plate being cold rolled can be observed periodically during the cycle, a camber can also be introduced during the cold-rolling steps. Usually, fluoroscopy is used to examine the core of the plate being cold rolled. However, due to the thin cladding and

*When two dissimilar materials are butted together, such as at the junction between the compact and picture frame, and then rolled, the material with lower density and lower high-temperature strength will tend to "ride over" the more resistant material. This is due to the fact that the material at the surface of a piece being rolled flows more than the material in the middle of the piece.

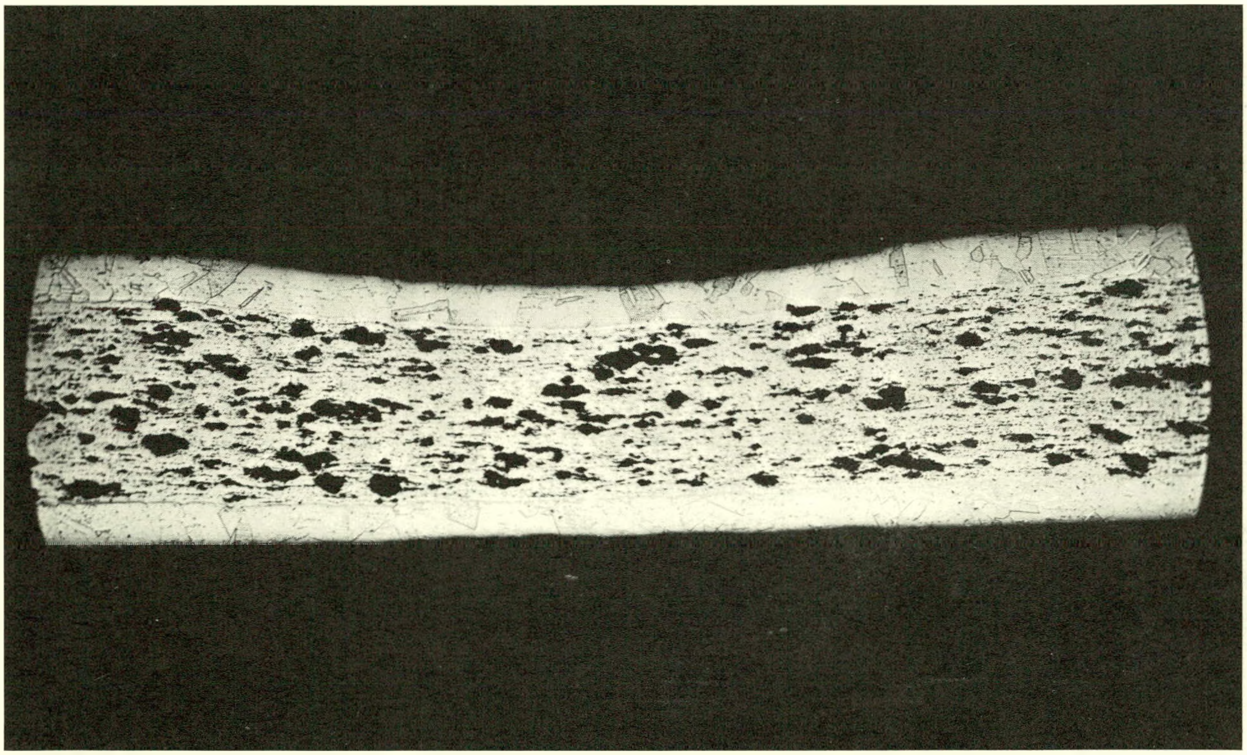
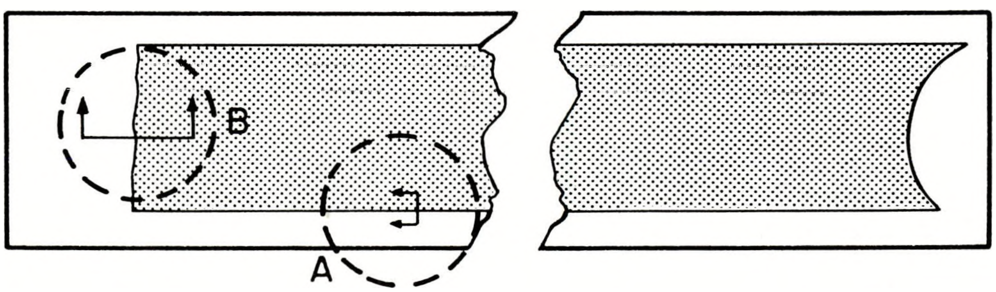


Fig. 22. Transverse Section of Fuel Plate Showing UO_2 Particles in Core and Surface Defect Which Occurred During Hot Rolling Operation

CUPPING OF CORE EDGE AT SIDE OF CORE IN FUEL PLATE;
SEE SECTION "A"

CUPPING OF CORE EDGE AT END OF CORE IN FUEL PLATE
SEE SECTION "B"



FUEL PLATE LAYOUT SHOWING POSITION
FROM WHICH SPECIMENS WERE TAKEN

Fig. 23. Fuel Core Edge Formations Caused by Rolling Process

hard core of the OMRE fuel plate, it was possible to see an image of the core while cold rolling. Figure 24 shows a typical example of a core image. The core image is caused by a 0.002-inch greater over-all thickness of the fuel plate over the core as compared to the thickness over the picture frame. Although it was not necessary, it was possible to intensify the core image by passing the plate between inked steel rollers.

B. FUEL BOX ASSEMBLY DEVELOPMENT

1. Fuel Box Welding Assembly Development

Initially, welding appeared to be an economical, positive method of assembling the fuel plates into the fuel box unit. In the original assembly concept, the fuel box consisted of two stainless-steel side plates and two stainless-steel end plates which were longitudinally welded to form the box. The 0.050-inch-thick side plates were longitudinally grooved 0.030 inches deep to receive the 16 fuel plates which were held in place by longitudinal welds bonding each fuel plate to the grooved side plate.

Previously, a proposal had been made that the fuel-element box assembly be accomplished by resistance-seam-welding flanged fuel plates to the side plates. A preliminary investigation disclosed that the seam-welding process could not be readily applied due to the space restrictions imposed by the 0.134-inch fuel-plate spacing.

Welding the fuel plates to ungrooved side plates was also investigated, but further work was discontinued because of the complicated fixturing requirements.

Fusion welding by use of the automatic-machine, inert-gas-shielded, tungsten-arc process appeared to be a logical approach to the problem of fastening the fuel plates in place. In the process, a continuous weld bead applied from outside the fuel box was used to join the fuel plates, inside of the box, to the side plates without the use of a filler metal.

a. Welding Equipment and Technique Investigation

The welding development was accomplished with a pneumatically-operated welding stake and an Air Reduction Heliweld Automatic Welding Head. The development work was done on 12-inch mock-ups using 0.030-inch-thick stainless-steel-clad fuel plates. The mock-ups were welded, as shown in Fig. 25, by

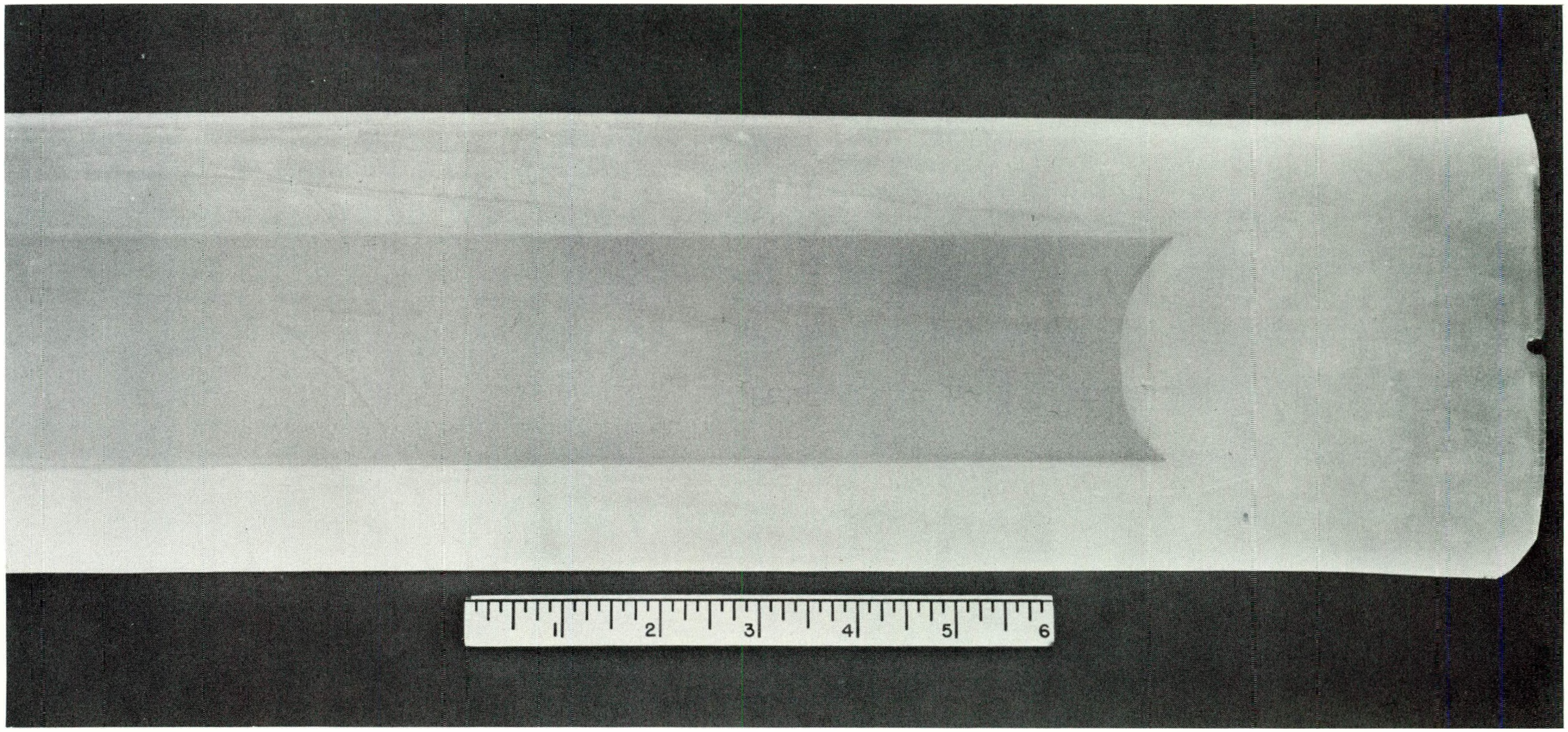


Fig. 24. Core Image on Cold Rolled Fuel Plate

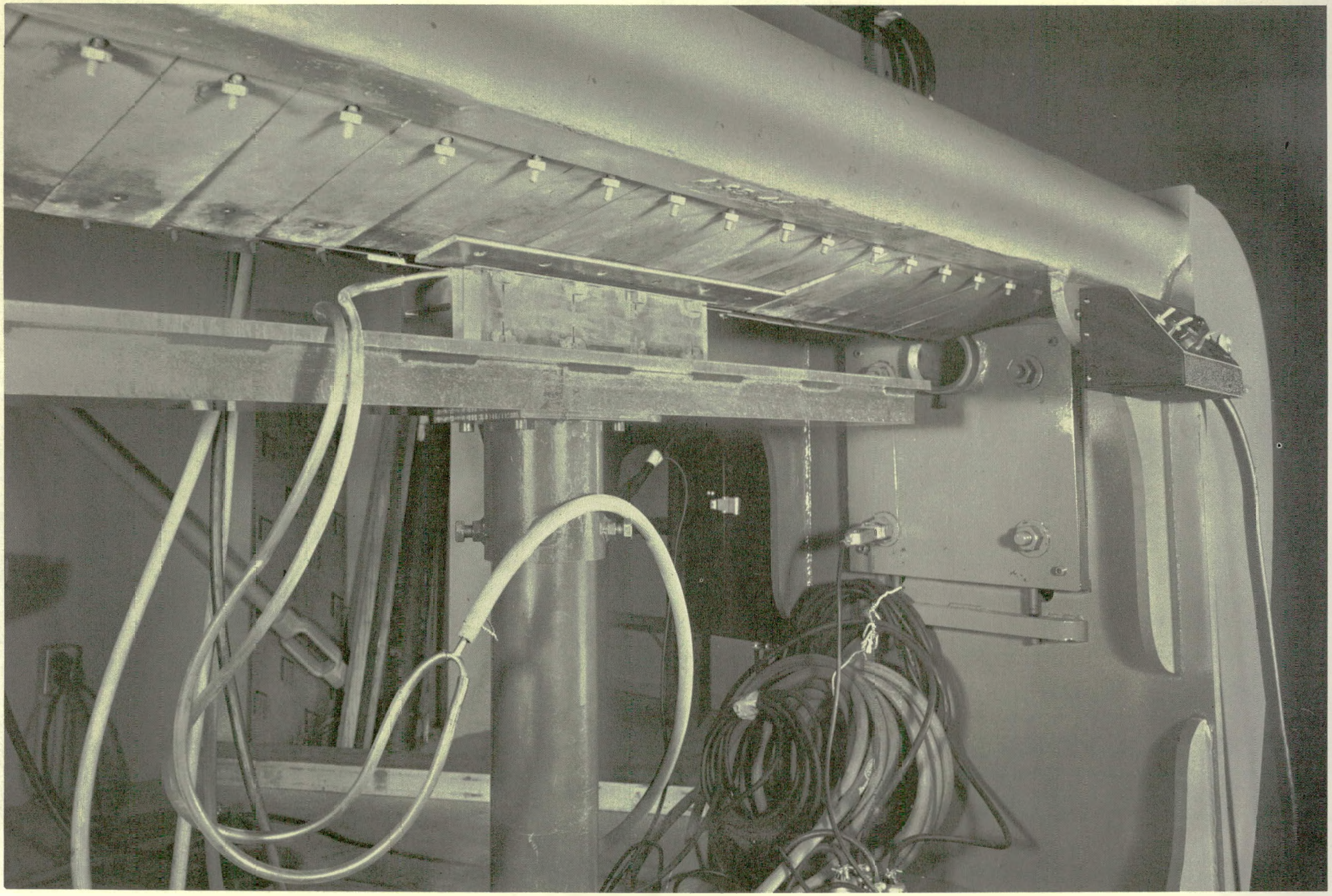


Fig. 25. Underneath View of Welding Stake Showing 12 Inch Developmental Fuel Box Being Welded With Inert Gas Back-Up

employing copper end-holding fixtures, through which a helium gas back-up was introduced into the fuel box assembly. The components of the fuel box were rigidly held together by the welding fixture shown underneath the welding stake. The fixture was designed for component alignment and subsequent tolerance maintenance during the welding operation. Hold-down fingers of the five-foot longitudinal welding stake straddle the joint to be welded.

Distortion of the fuel box components was the primary problem encountered during the welding development program. Later it was found that thermal stresses possible in the fuel box during reactor operation presented a weld shearing problem. The following investigations were made to minimize component distortion and to obtain a fuel box with a high inherent strength that would overcome the thermal stresses:

1) Use of weld-chilling techniques.

2) Use of spot welds and other methods to reduce weld area.

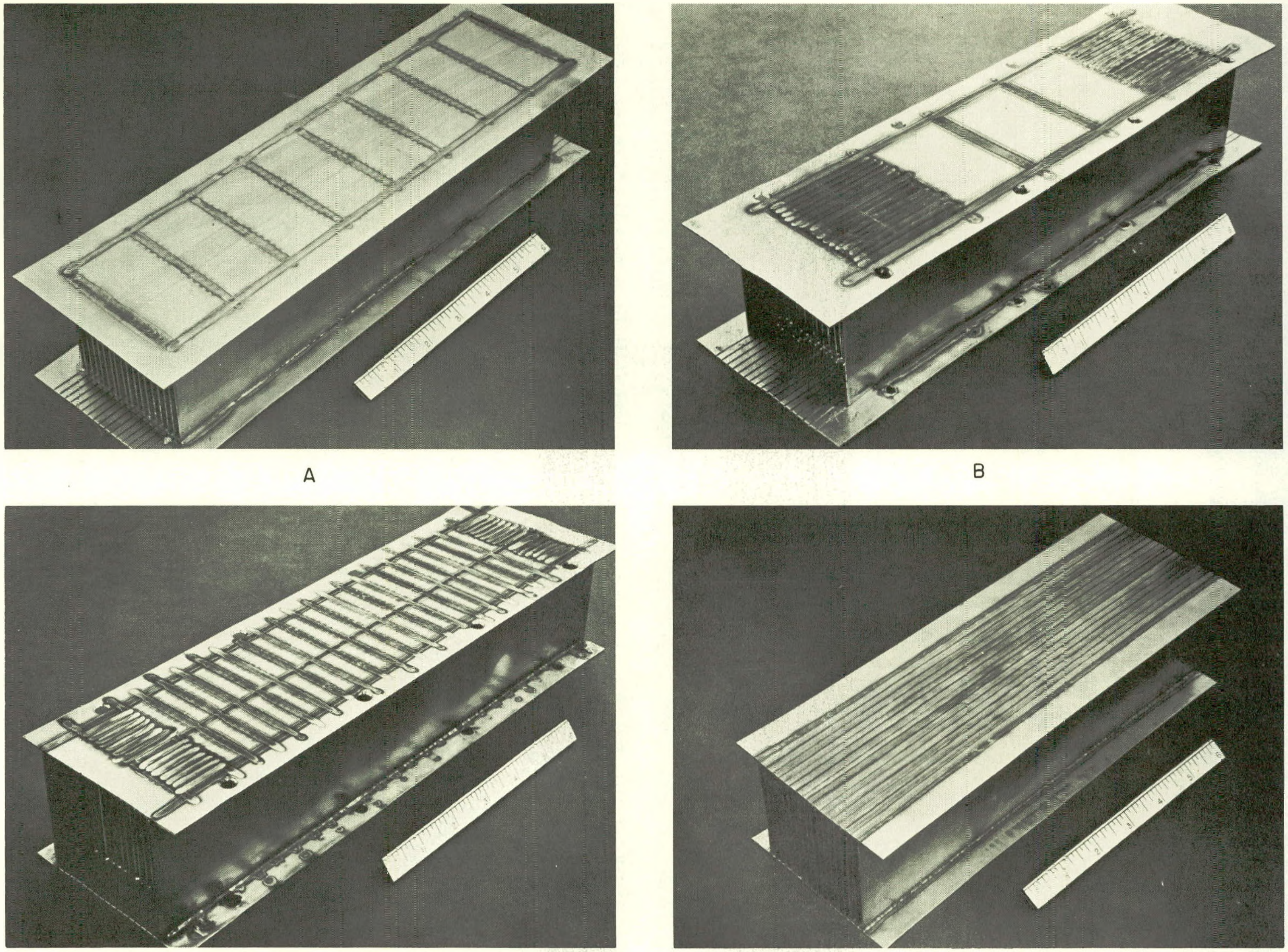
3) Use of various weld bead patterns.

The first fuel box mock-up, assembled by continuous longitudinal fusion weld beads above each fuel plate, as shown in Fig. 26, D, resulted in considerable distortion in the components. Further tests showed that the distortion could not be reduced sufficiently to produce a usable fuel element.

A method of minimizing distortion is to reduce the weld area as shown in the mock-up in Fig. 26, A. The spaced, transverse weld beads contact each plate and function as spot welds.

b. Weld-Chilling Techniques

The fuel box mock-up illustrated in Fig. 26, A was welded without copper chilling plates between the fuel element plates so that a determination could be made of the extent of maximum distortion resulting from normal weld shrinkage. Considerable distortion occurred in the end plates which form two sides of the fuel box and somewhat less distortion occurred in the fuel plates. Destructive inspection of the joints disclosed good weld penetration with a slight amount of weld metal drop-through. The introduction of solid copper chilling plates in the spaces between the fuel plates reduced the distortion approximately 50 per cent.



A B

C D

Fig. 26. Weld Bead Patterns Used to Fasten Components of Developmental Fuel Boxes

The solid copper chill plates, discussed above, did not permit an intimate contact between the fuel plates and chill plates due to necessary clearances. Two copper plates in each space between the fuel plates permitted a more intimate contact with better heat flow from the fuel element components to the copper chills. Distortion was reduced considerably with the split chill bars.

Water was also investigated as a chilling medium by immersing all of the fuel box, except for the plate being welded, in a water bath. The plate distortion was the same as that obtained with copper chill plates, and inspection of the weld root faces indicated that gas absorption had caused considerable oxidation.

c. Spot Welds

To further reduce plate distortion, helium-shielded, tungsten-arc spot-welding equipment was obtained. The resulting spot welded fuel box (shown in Fig. 27) had a minimum amount of plate distortion, which was well within the limits given in the fuel element specification.

d. Weld Bead Pattern

At this time, the results of the preliminary analysis of the stresses occurring within a fuel element cooled by a polyphenyl were completed. As previously discussed in Section V-B, the results indicated that the stresses occurring within the fuel element during reactor operation would be large enough to cause the welded joints to shear. The fuel boxes in Fig. 26 show welding patterns used to increase the strength of the fuel box assembly without materially increasing the distortion of the fuel box components. However, the final results of the stress analysis indicated that further development effort was not justified. The results showed that continuous longitudinal weld beads at each fuel plate was the only method that would result in a sufficient safety factor against fuel element failure caused by shearing stresses. It should be pointed out, however, that the use of a fuel element box assembled by using spaced, continuous transverse weld beads or spot welds might be useful in a reactor cooled by a material having good heat transfer properties such as water.

2. Fuel Box Brazing Assembly Development

Assembly of the fuel element by brazing techniques was carried on concurrently with the welding development. As in the welding development program, 12-inch long stainless-steel mock-ups were used for the brazing studies.

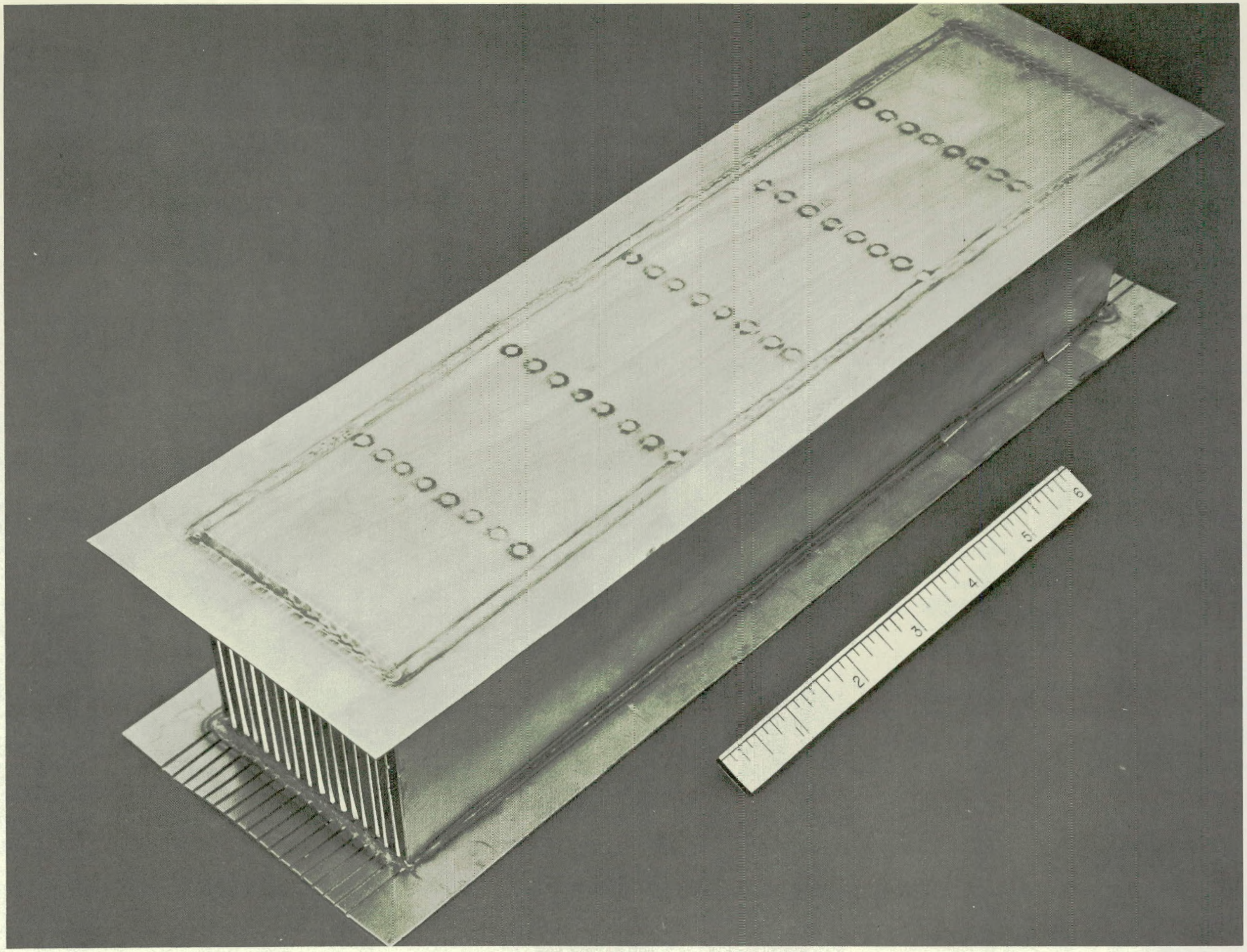


Fig. 27. Welded Fuel Box Assembly Mock-Up Using Transverse Spot Welds to Hold Fuel Plates in Place

The mock-ups were brazed in a graphite fixture consisting of two channel-like top and bottom plates and two rectangular side plates. Electrolytic copper was chosen as the brazing alloy.

The copper in the form of 30-mil-diameter wire was clipped to each joint by bending the ends of the wire over the ends of the fuel plates. The fuel boxes were brazed in a dry hydrogen atmosphere. The hydrogen chemically reduced the metallic oxides without the use of flux and promoted the formation of a scale-free surface.

a. Fixture Design

Two main problems presented themselves during the brazing development program which pertained to fixture design:

1) The difference between the thermal expansion of the graphite fixture and the fuel box being brazed, which caused the fuel plates to bow or drop out of the retaining grooves.

2) Temperature differences in various parts of the assembly, which resulted in bowing due to thermal stresses.

Because of the variation reported in values for the coefficient of expansion for graphite, the expansion was determined experimentally for the material used for the fixture. The allowance for the expansion resulted in a sufficiently large clearance between the fixture and the fuel box at ambient temperatures to permit the fuel plates to drop out of the retaining grooves. To overcome this, the fuel plates were retained in the grooves of the side plates by binding the assembly together with copper wire. As the temperature during the brazing operation was increased, the copper wire became sufficiently plastic to allow the fuel element components to expand against the graphite fixture. At brazing temperature (2050° F) a clearance of five mils existed between the fuel box and the graphite fixture. The fixture that was used for successfully brazing a full-length fuel box is illustrated in Fig. 28.

b. Fuel Plate Orientation

Different fuel plate orientations were also tried during the brazing fixture development phase. In the method discussed above, the fuel box was

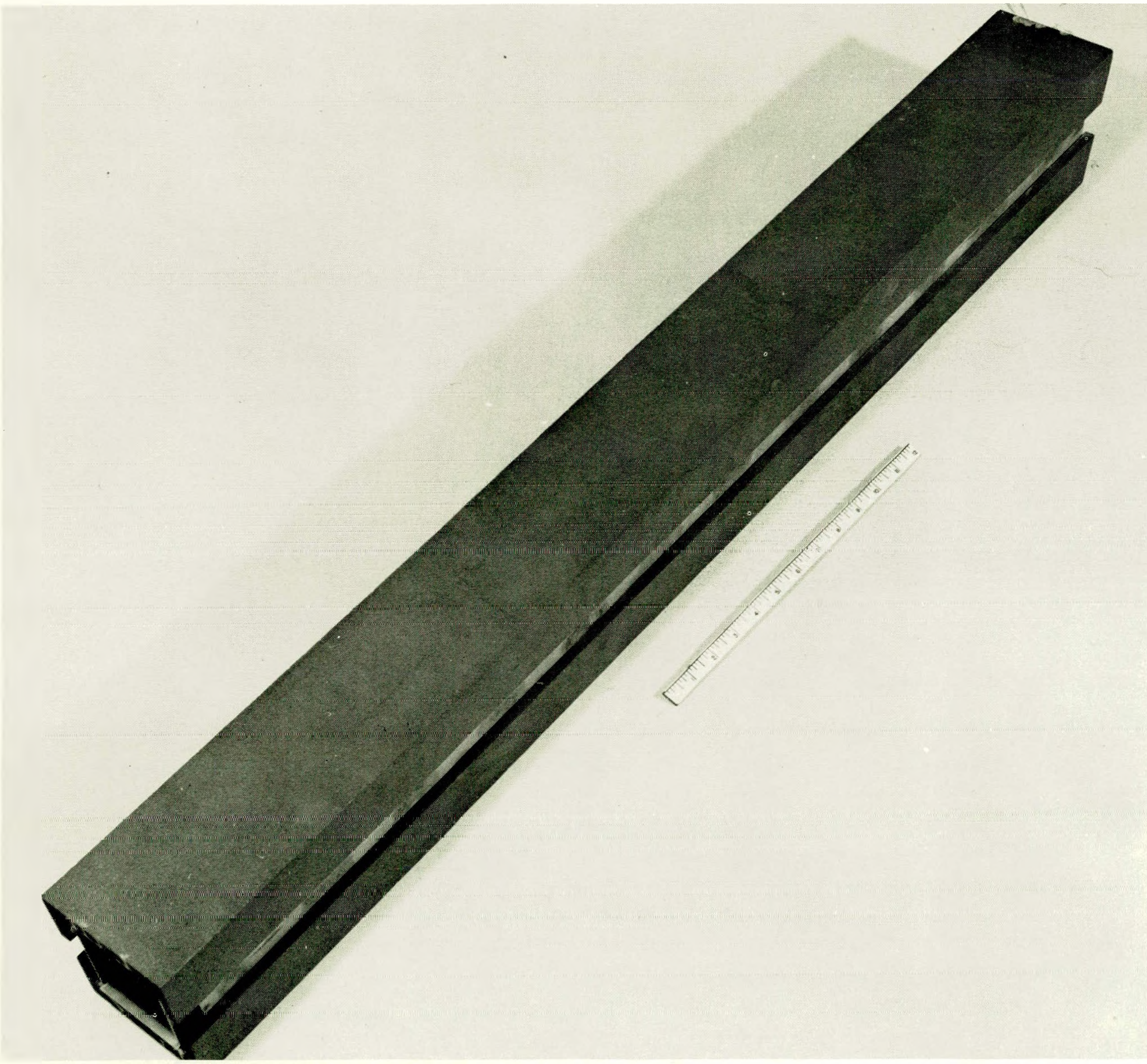


Fig. 28. Brazing Fixture

positioned in the fixture so that the width of the fuel plates was oriented horizontally. As the fuel box components expanded, the grooved side plates moved horizontally to a fixed graphite fixture wall. A fixture was also designed so that the fuel plates were oriented vertically. The top of the fixture was movable. At room temperature, the fixture top rested on the grooved side plate, thus retaining the fuel plates in the grooves. As the temperature of the assembly was raised to the brazing point, the top of the fixture moved with the expanding fuel box components. Although successful mock-ups were brazed with the "vertical plate" fixture, difficulty was experienced in placing the filler material in the upper fuel plate-to-grooved plate joints. Grooved side plates fabricated from a bimetal of copper on stainless steel would probably solve the problem of placing the brazing material at the joints. Such side plates with preplaced copper would also facilitate brazing fuel boxes in the "horizontal plate" fixture.

C. FUEL PLATE MOCK-UP BRAZING STUDIES

The brazing development studies were conducted on fuel box mock-ups assembled of all-stainless-steel fuel-plate mock-ups. Some doubt existed as to whether fuel plates containing UO_2 would behave in the same manner as the stainless-steel mock-ups. Brazing tests with plates containing depleted UO_2 disclosed that no additional distortion was contributed by the UO_2. An end view of successfully brazed full-length fuel box containing depleted UO_2 plate is shown in Fig. 29.

VII. NON-DESTRUCTIVE INSPECTION

It was desirable that the fuel plates be non-destructively inspected for the following parameters:

1) Location and straightness of the fuel-bearing core.

2) Thickness of the stainless-steel cladding over the core.

3) Cladding-to-core and frame bond.

4) Uniformity of the distribution of the UO_2 in the core.

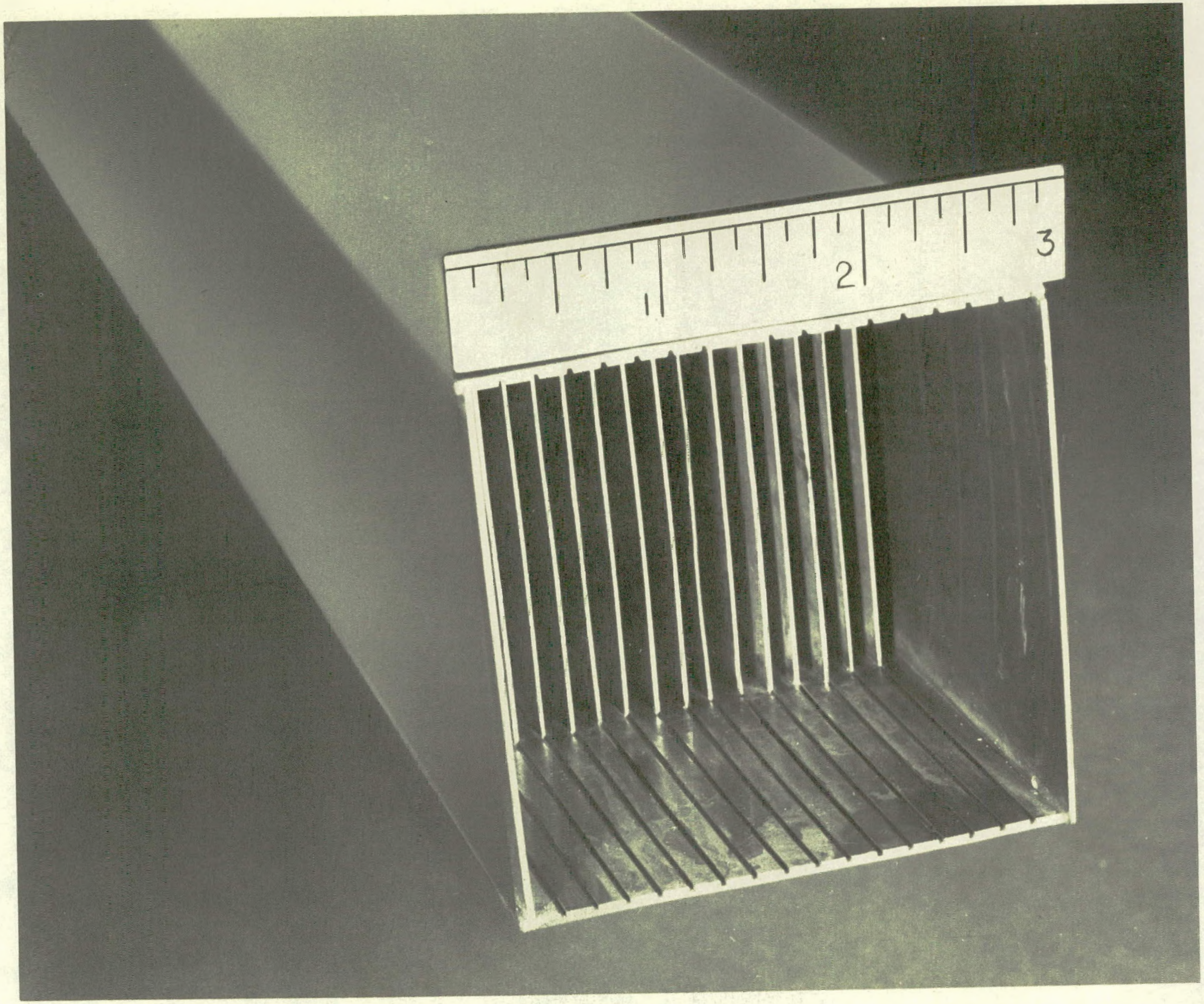


Fig. 29. End View of Full Length Brazed Fuel Element Containing Plates Loaded With Depleted UO_2

A. CORE LOCATION AND INSPECTION

Prior to shearing and machining, the core of the fuel plate had to be inspected for straightness and then located with respect to some external reference mark in order to carry out the machining operations. After machining, the plate had to be inspected to ensure that the core was centered within the fuel plate. Radiography proved to be a relatively simple solution to the problem. It was found, however, that the fuel plates had to be clamped to the film holders to ensure an accurate image of the plates. The films were placed in radiographic-grade cardboard film holders. No intensifying screen was used to provide a uniformly exposed film. A curved fixture was constructed to hold all parts of the film equidistant from the target in the X-ray tube. A practical working distance of the film from the target was found to be 60 inches. The film was exposed for 45 seconds at 150 kilovolts. To make certain no dimensional changes occurred in the film between exposure and use, humidity conditions to which the film was subjected were closely controlled. Under adverse humidity conditions, film shrinkages up to 1/4 inch in 24 inches were observed. This shrinkage is characteristic of acetate-base films, which is the type that was used.

B. CLADDING THICKNESS DETERMINATION

The process specifications called for a cladding thickness control of plus or minus one mil. A greater variation might have jeopardized the continuity of the cladding and also affected the rate of heat conduction through the cladding.

Determination of the cladding thickness by ultrasonics was investigated. It was found that no commercially available ultrasonic instrument was capable of measuring the cladding thickness. Because of the low cladding thickness of five mils and a necessary resolution of better than one mil, a very high frequency was necessary. No transducers were available that would operate in the 40 to 50 megacycle range, and the stability of the transducer driving equipment was not sufficient for the less than one mil resolution.

During the plate fabrication feasibility studies, it was found by destructive inspection that the variation of cladding thickness was less than 1/2 of a mil within a batch. Due to the close cladding thickness tolerances that were inherent in the fabrication process, the search for a device that would measure cladding thickness was halted and the cladding thickness checks were made by sectioning rejected fuel plates from each batch.

The sectioned plates were also examined for core thickness and possible UO_2 "stringering." "Stringering" occurs when a UO_2 particle breaks down during the rolling process into a long stringer of parts of the broken particle. Stringering causes undesirable particle size changes and can affect the uniformity of distribution of UO_2 in the core.

C. CLADDING-TO-CORE BONDING

To achieve the necessary heat transfer rates from the core to the cladding and then to the polyphenyl coolant, it was imperative that the cladding be metallurgically bonded to the core. Bonding was also necessary between the cladding and the stainless-steel frame around the core to ensure that no fission products would reach the coolant stream.

A heat transfer analysis was made to determine how large an unbonded area could be tolerated before the resulting hot spot would cause the coolant to decompose and foul the fuel plate with decomposition products. Such fouling would further aggravate heat transfer problems. It was decided to base the calculations on a maximum temperature rise of 10° F.

The calculations showed that a large temperature rise occurred on the surface of the cladding opposite the unbonded area. A smaller temperature rise occurred around the periphery of the unbonded area. The data indicated that a circular unbonded area of 1/16-inch diameter would produce a maximum temperature rise of 10° F.

Unbonded Area Detection

The following methods of detecting unbonded areas in fuel plates were examined to determine whether they would detect an unbonded area less than 1/16 inch in diameter:

1) Heat-transfer methods
   a) Frost test
   b) Red-heat method
   c) Use of temperature indicator

2) Eddy current

3) Ultrasonics

a) Transmission method

b) Reflection method

c) Shadow method

A literature survey was made to determine which one of the methods appeared to be the most feasible.

1. Heat-Transfer Methods

Heat-transfer methods appeared to be attractive because large areas could be examined quickly and permanent records were easily obtained. However, the methods were not sensitive enough to detect, with accuracy, unbonded areas less than 1/16 inch in diameter. In the three methods, the plate is heated and the areas that are not bonded are detected due to their low heat transfer properties. For the frost test, the plate is coated with acenaphthene, which is white and opaque when applied and which melts to a transparent fluid. Temperature indicators are used in a similar manner, in that they will change colors due to temperature and indicate any hot spots. For the red heat method, the plate is heated to red heat and low-heat-transfer unbonded areas are viewed as dark spots.

2. Eddy-Current Method

The use of eddy-current methods of detecting unbonded areas was not attractive because of the slow scanning required and because of the need for development of a special probe. Also, the method did not appear to have enough sensitivity.

3. Ultrasonics

The use of ultrasonics for detecting unbonded areas has been well established commercially. However, the cladding presented a special problem due to its thinness. The through-transmission method which required a transmitting and receiving transducer was ruled out because of the difficulty of obtaining a collimated ultrasonic sound beam with uniform cross-sectional area. The reflection method (where an echo is received from the back surface of the part being tested) was also ruled out because the frequency required for this method is beyond the present state of the art.

The shadow method of detecting flaws, which depends upon the *lack* of reflected energy from the *front* surface being inspected, appeared to be promising and was therefore investigated thoroughly for this application. The method was developed by the Research Division of Automation Instruments Inc. of Boulder, Colorado.

a. Ultrasonic Bond Inspection by the Shadow Method

The shadow method involved the transmission of a converging ultrasonic beam through the specimen to be tested. The diameter at the focal point of the beam was about 1/16 inch. Water was used as a coupling medium through which the beam was transmitted from the crystal to the test specimen. The lithium sulfate crystal was operated at a frequency of 15 megacycles. The crystal not only generated the ultrasonic beam but focused it as well. A properly shaped crystal was prerequisite for producing the sharply focused beam that was found to be necessary to differentiate between bonded and unbonded areas.

One of the most difficult problems was the production of test specimens with known and controlled unbonded areas. The preliminary survey testing was done with a 30-mil-thick fuel plate containing depleted UO_2 in the core. One-eighth-, 1/16-, and 1/32-inch-diameter holes were drilled through the cladding of one side of the plate and through the core to the cladding on the other side. The five-mil cladding on one side of the plate was left intact. Attempts were made to produce unbonded areas by placing foreign material on top of the fuel core in the sandwich before hot rolling. Unfortunately, either no detectable unbonded areas were produced or the areas were so large in size that they were not usable.

No difficulty was experienced in detecting the 1/8- through 1/32-inch holes in the drilled test plate. However, some doubt existed as to validity of the drilled test plate results when applied to an actual unbonded area on a fuel plate. A plate containing an unbonded area which ran longitudinally in the cladding over the center of the core was finally produced. The width of the flaw varied from 1/16 inch to 1/8 inch. The flaw was visually detectable.

The flaw was scanned with the ultrasonic beam longitudinally, transversely, and diagonally. Indications of the unbonded area were always clearly apparent on the display oscilloscope.

A group of 10 fuel plates were examined with the "shadow method" ultrasonic instrument. About two plates per hour could be 100 per cent scanned for cladding defects with automatic equipment. Visible flaws were always detected. However, some apparent flaws were detected by the instrument which could not be found by metallographic examination of the areas. It was also found that the instrument was very sensitive to the surface condition of the fuel plate. From this test, it was decided that the method was not 100 per cent reliable.

With the above factors in mind, it was decided to use the "blister anneal" as a method of detecting bonding flaws.

It should be pointed out that with more developmental effort, the shadow method of ultrasonic examination of fuel plates for cladding defects might prove to be very attractive, since no particular skill or experience is required to interpret the results of the examination. This method might also reveal small doubtful defects that might not appear in the blister-anneal test.

b. Blister-Anneal Test

In the blister-anneal process, the fuel plate is heated to 2000° F and held at that temperature for two hours. Unbonded areas form a visible blister. Although the blister anneal process is a destructive form of bond testing, it has the following advantages:

1) It merely extends the annealing step that is necessary after the cold-rolling operation.
2) Many plates can be tested at one time.
3) Fuel plates with unbonded area have to be rejected, so that the destructive nature of the test is of no consequence.

D. UNIFORMITY OF UO_2 DISTRIBUTION

Uniform distribution of the UO_2 in the fuel core was necessary in order to prevent localized hot spots which might cause decomposition of the coolant. Heat transfer calculations indicated that it was desirable to limit the variation in UO_2 distribution to within 5 per cent. The allowed variation in distribution was based on a 1/8-inch-diameter area, which meant that the UO_2 content of any 1/8-inch spot on the plate should not vary more than 5 per cent by weight when compared to any other 1/8-inch spot on the same or other fuel plates.

Variations in UO_2 distribution in the finished fuel plate are primarily caused by incomplete blending of the UO_2 and stainless powders that were used for the fuel core. However, variations in UO_2 distribution can also be caused during the handling of the blended powders, by variation in the thickness of the pressed compact, by "stringering" or the breaking up of UO_2 particles during the hot-rolling operation, and by variations in the fuel core thickness induced during the hot-rolling operation.

1. Methods Investigated

The following non-destructive methods of examining fuel plates for variation of UO_2 distribution were investigated:

a) Radiography

b) Autoradiography

c) Radiation gage

As previously discussed, radiography was used to locate the core for the machining operations. It was also possible to use the same radiographs to determine the uniformity of UO_2 distribution. Tests showed, however, that very close exposure and film development controls were necessary in order to achieve reproducible negatives that could be used for UO_2 distribution inspection. Also, difficulty was encountered in obtaining uniformly-exposed negatives due to a variation in the strength of the flux in portions of the radiation field from the X-ray source, which made the use of control negatives very difficult.

With autoradiography, the UO_2 in the fuel core was used as a source of radiation for exposing the film. It was found that exposures of more than 10 hours duration were necessary to sufficiently expose the film. This, of course, would cause delays in production which could not be tolerated.

Due to the above difficulties, a radiation gage was constructed to determine the uniformity of UO_2 distribution in the fuel plates. However, the radiographs that were obtained for core location were also used to determine if gross non-uniformity of UO_2 distribution occurred within any one fuel plate.

2. Radiation Gage

A radiation gage,[3] illustrated in Fig. 30, was used to determine the uniformity of UO_2 distribution of the fuel plates. The instrument consisted

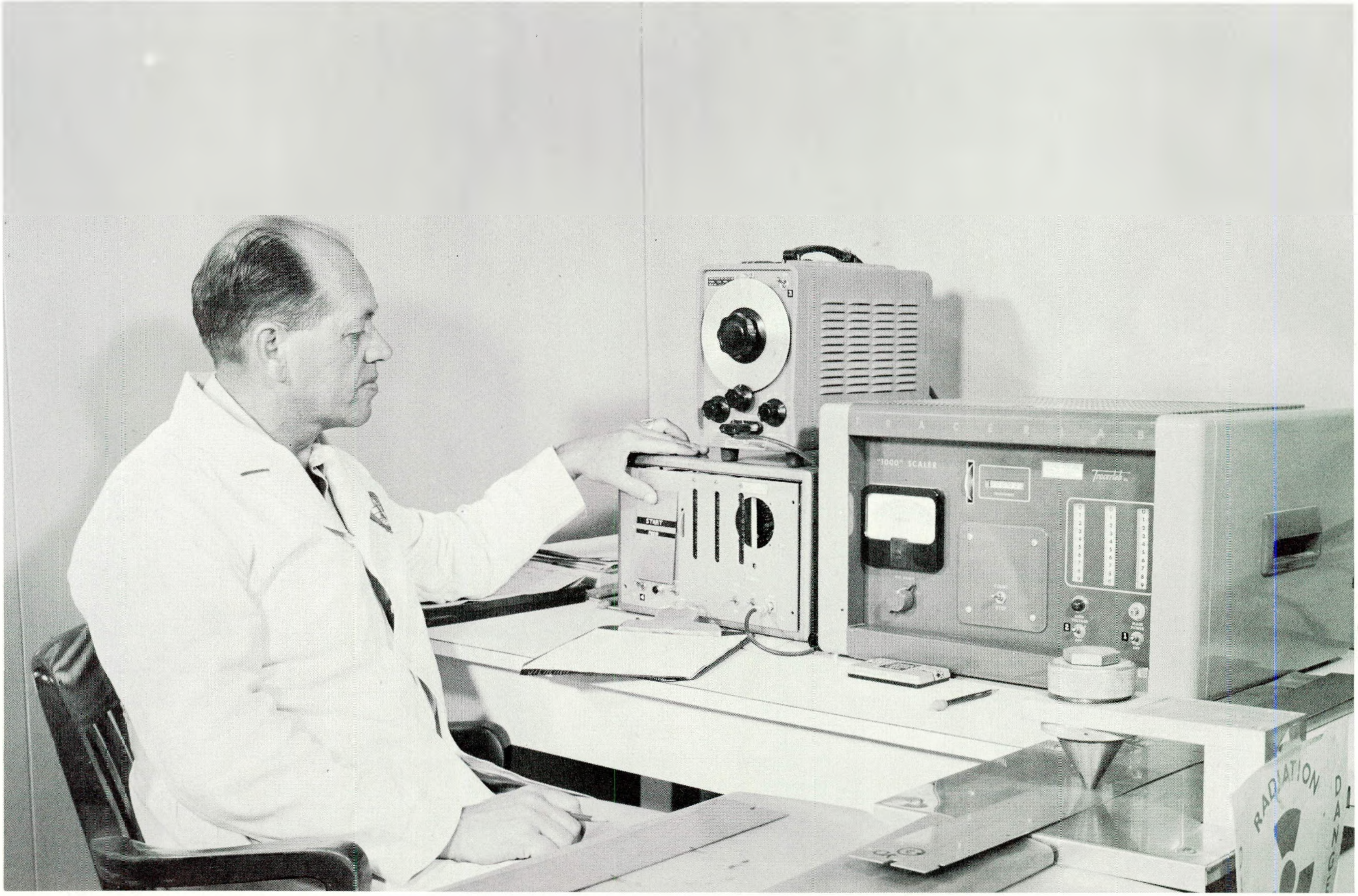


Fig. 30. Non-Destructive Inspection of Uniformity of UO_2 Distribution in Fuel Plate

of the following components:

a) A radioactive source enclosed in a collimating head.

b) A radiation detection system.

c) A radiation measuring or counting circuit.

d) A time base for the counting circuit.

The distribution of UO_2 in the fuel plates was checked by placing the plate underneath the collimating head containing the radioactive source and measuring the attenuation of the 1/8-inch-diameter radiation beam as it passed through the plate.

a. Collimating Head

After examining the characteristics of available radiation sources, cerium-144 having a strength of two millicuries was chosen. The cerium is a 60-day half-life gamma emitter, with a principal gamma energy of 0.134 Mev. The low-energy gamma radiation results in a selective absorption by the uranium in the fuel core with a lower absorption by the stainless steel. A 3.1-Mev beta emanation from the source was reduced with a graphite absorber. The absorber also served to bring the 10,000 counts per second from the source down to a usable value of 5000 counts per second. In the original concept, the thickness of the absorber was to be reduced as the source decayed so as to keep the count per unit time constant. However, it was found that a ratio of the count in the air (without passing the radiation through a plate) to the count through the plate was a more usable control.

The source and absorber were contained in a brass collimating head that collimated the radiation beam to an 1/8-inch diameter circle. The collimating head can be seen above the fuel plate being checked in Fig. 31.

b. Radiation Detector

After passing through and being attenuated by the plate the collimated gamma beam was directed through another collimator to a scintillation crystal. The second collimator prevented any scattered radiation from reaching the crystal.

The output of the scintillation crystal was measured by a photomultiplier tube and associated amplifying circuits. Originally, only superficial radiation

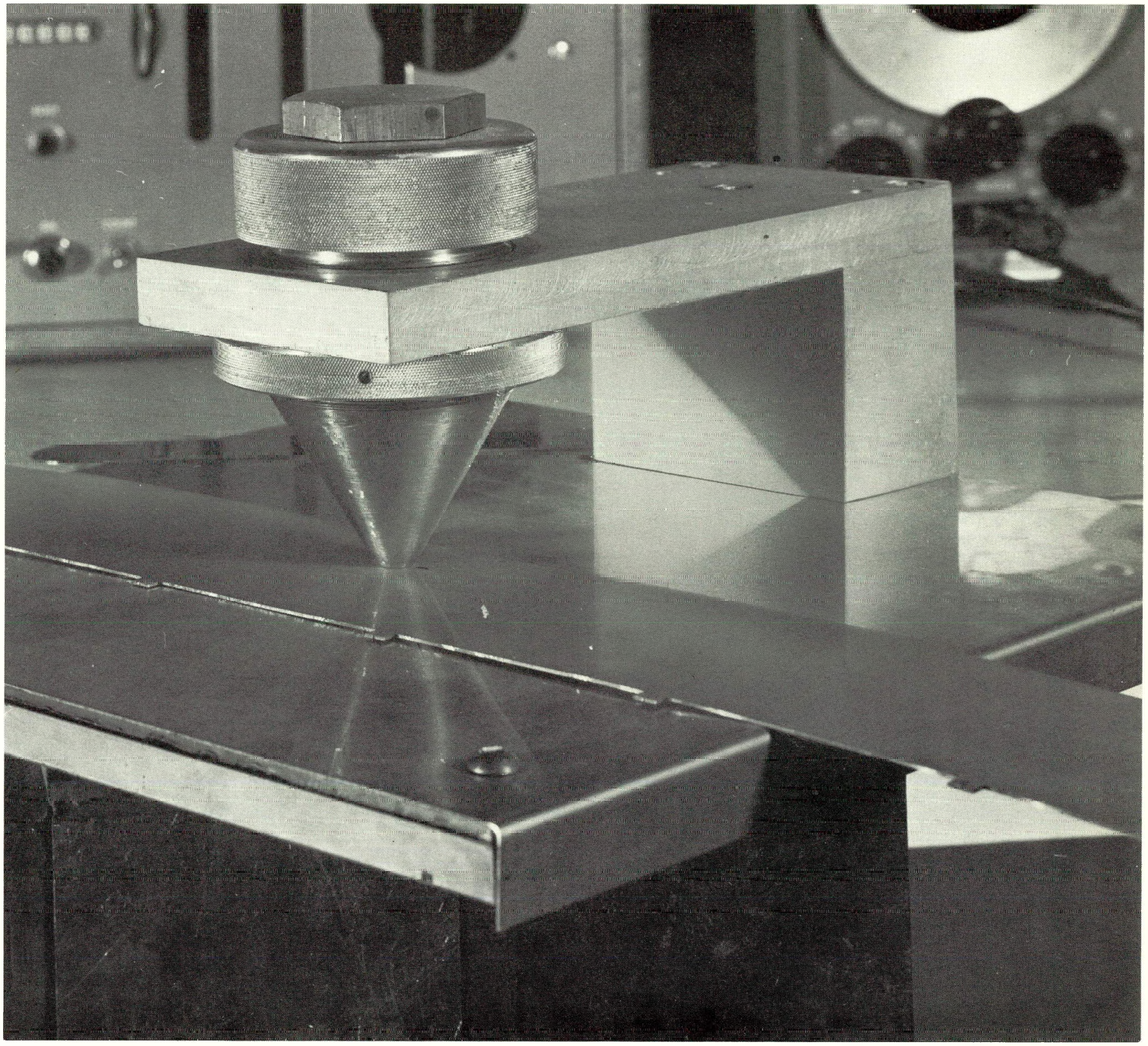


Fig. 31. Collimating Heat of Radiation Gage

shielding was used around the detection system. However, considerable radiation was detected from the plate being measured and other fuel plates in the vicinity which resulted in a masking of the desired radiation. A substantial lead shield permitted the unobstructed measurement of the attenuated gamma beam passing through the plate.

c. Rate Detection

A Tracerlab digital counter was used as a rate detector. The resolution time of the counter was one microsecond, which permitted a percentage error of the observed count of approximately 0.5 per cent. An oscillator and another digital counter furnished the time base for the rate detector. Counting times of approximately 30 seconds were found to be necessary to achieve sufficient accuracy.

d. Calibration

Considerable difficulty was experienced in calibrating the radiation gage due to the small size of the area being measured in the fuel plate. It was almost impossible to produce a standard fuel plate with a guaranteed known composition within any 1/8-inch diameter area on the plate due to the difficulty of measuring the area with means other than the radiation gage. Through chemical analysis by the X-ray Fluorescence Method[4] an approximate calibration was achieved. One-inch-square sections of fuel plates were scanned with the radiation gage, after which the samples were analyzed for their UO_2 content.

e. Statistical Analysis

Before the radiation gage was calibrated, there was some question as to whether batch blends of the stainless steel and uranium oxide powders for one entire element were more desirable for core homogeneity than were individually blended powders for the core of each plate.

Thirty radiation gage readings per plate were taken on plates made by each of the two blending processes. The analysis of the readings indicated that the batch blending method was somewhat better than the individual blending method.

Thirty readings per plate were made on all the plates used in the elements for the reactor. A statistical analysis is in progress on the results. The analysis should indicate the following:

1) The relative magnitudes of the variability between plates and the variability within plates.

2) The absolute variation of the uranium density in the fuel plates.

3) The magnitude of the inherent or experimental error of the radiation gage.

VIII. INSTRUMENTATION OF FUEL ELEMENTS

The fundamental objective of the OMRE is to obtain data on the behavior of organic coolants in a reactor core. Thermal and radiolytic decomposition of the organic coolant will result in the formation of decomposition products which may deposit on the fuel plates. The resulting increased resistance to heat flow will cause an increase in the surface temperature of the fuel plate with a resultant increase in thermal decomposition of the coolant. Fuel plate surface temperature measurements present an excellent method of obtaining continuous heat transfer data from the reactor core. Such measurements can also be used for reactor control. Thermocouples appeared to be the only practical method of obtaining the fuel plate surface temperature.

A. THERMOCOUPLE REQUIREMENTS

In order to obtain a representative surface temperature measurement, a thermocouple installation on the fuel plate must meet three stringent requirements:

1) The thermocouples must measure accurately the temperature at the point of attachment or be capable of being calibrated.

2) The thermocouples must be attached to the fuel plate in such a manner as to minimize local disturbances of the thermal pattern and yet resist detachment from the plate by the turbulent coolant stream.

3) The thermocouples must cause as little interference as possible to the coolant flow pattern.

After consideration of the above points, a development program resulted in the following method of thermocouple attachment.

A chromel-alumel thermocouple with five-mil-diameter (36-gauge) wire was chosen. The wires were insulated from one another by compressed magnesia powder and were encased in a 10-mil-thick 1/16-inch-diameter stainless-steel sheath. The sheath and MgO were removed and the base wires were attached to plates by welding. The bared wires were insulated from one another and from contact with the coolant flow by 0.010- to 0.012-inch-diameter quartz sleeves. The sheathed thermocouples were held in place on the fuel plate by small stainless-steel clips welded to the plate.

Seven instrumented fuel elements are to be installed in the first core loading. Each element will have five thermocouples. Three of these thermocouples will measure the *surface temperature* of the fuel plate. The other two thermocouples will measure the exit *bulk coolant temperature* near the mid-point and side of the channel adjacent to the hottest fuel plate. Figure 32 shows the location of the thermocouple on the fuel plate and the inset shows the method of attaching the couple to the plate.

B. ATTACHMENT METHODS

Three other methods of attachment were tested in a thermal loop which contained polyphenyl at 500° F, the temperature expected during reactor operation. In all cases, the sheathed thermocouple wire was held in place by metal clips. The methods of attachment differed only in the area of the thermocouple junctions.

In the first method, the bared thermocouple leads from the sheath to the welded junction were encased in quartz tubes. In the second method, a welded thermocouple junction was staked into 1/4-inch-diameter copper disks which were brazed to the fuel plate. The purpose of the copper disk was to supply an amount of heat to the junction sufficient to compensate for the heat loss due to conduction to the coolant stream along the thermocouple leads. The third method consisted of a nickel-plated ceramic coating which covered thermocouple wires that were previously welded to the plate. This method was abandoned because of difficulty in fabrication and possible failure due to spalling of the ceramic.

C. TEST APPARATUS DESCRIPTION

The apparatus for comparing the thermocouple attachment methods is shown in Fig. 33. It consisted of a simulated fuel box channel formed by welding two

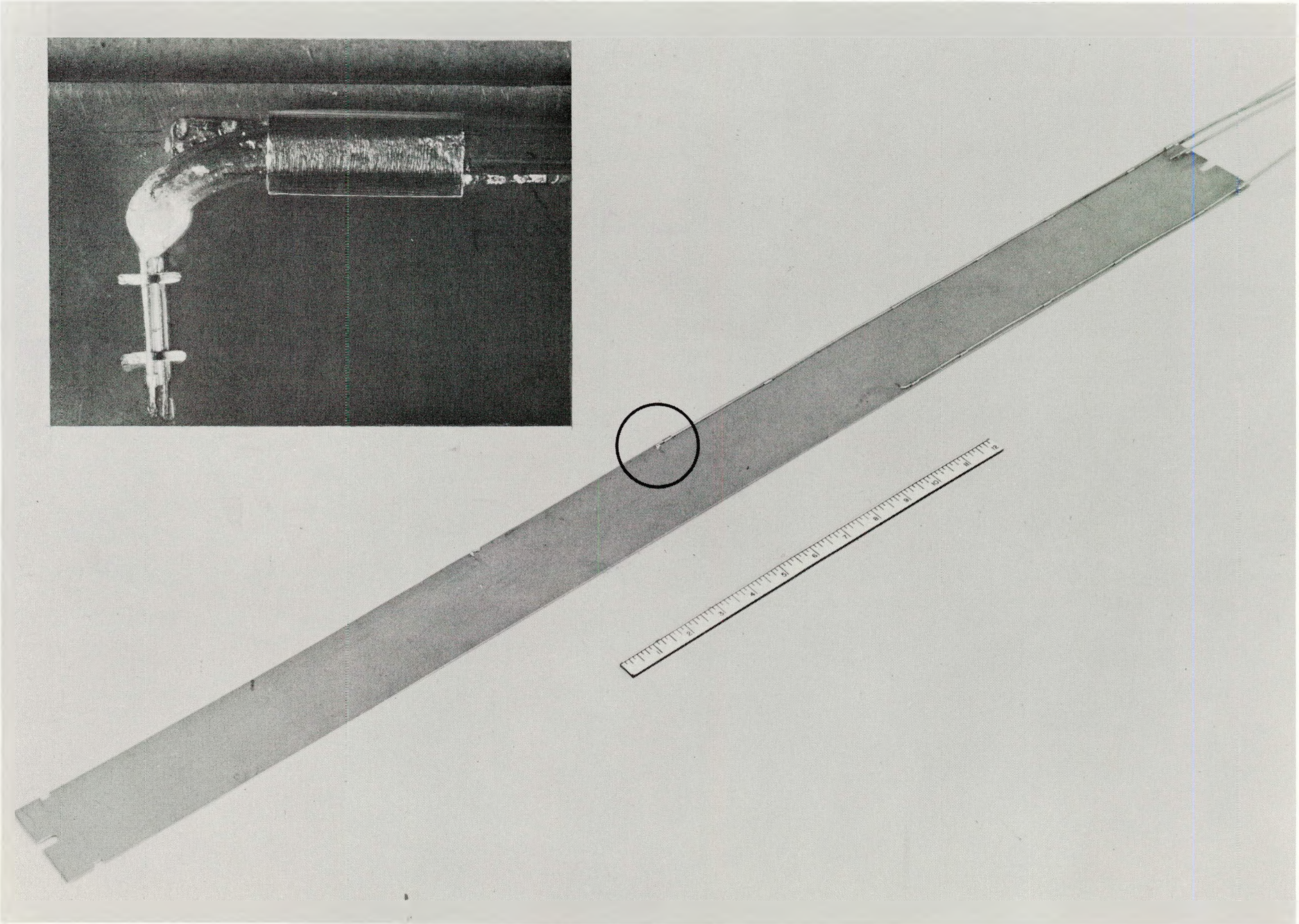


Fig. 32. Fuel Plate With Attached Thermocouples With Close-Up of Attachment Method

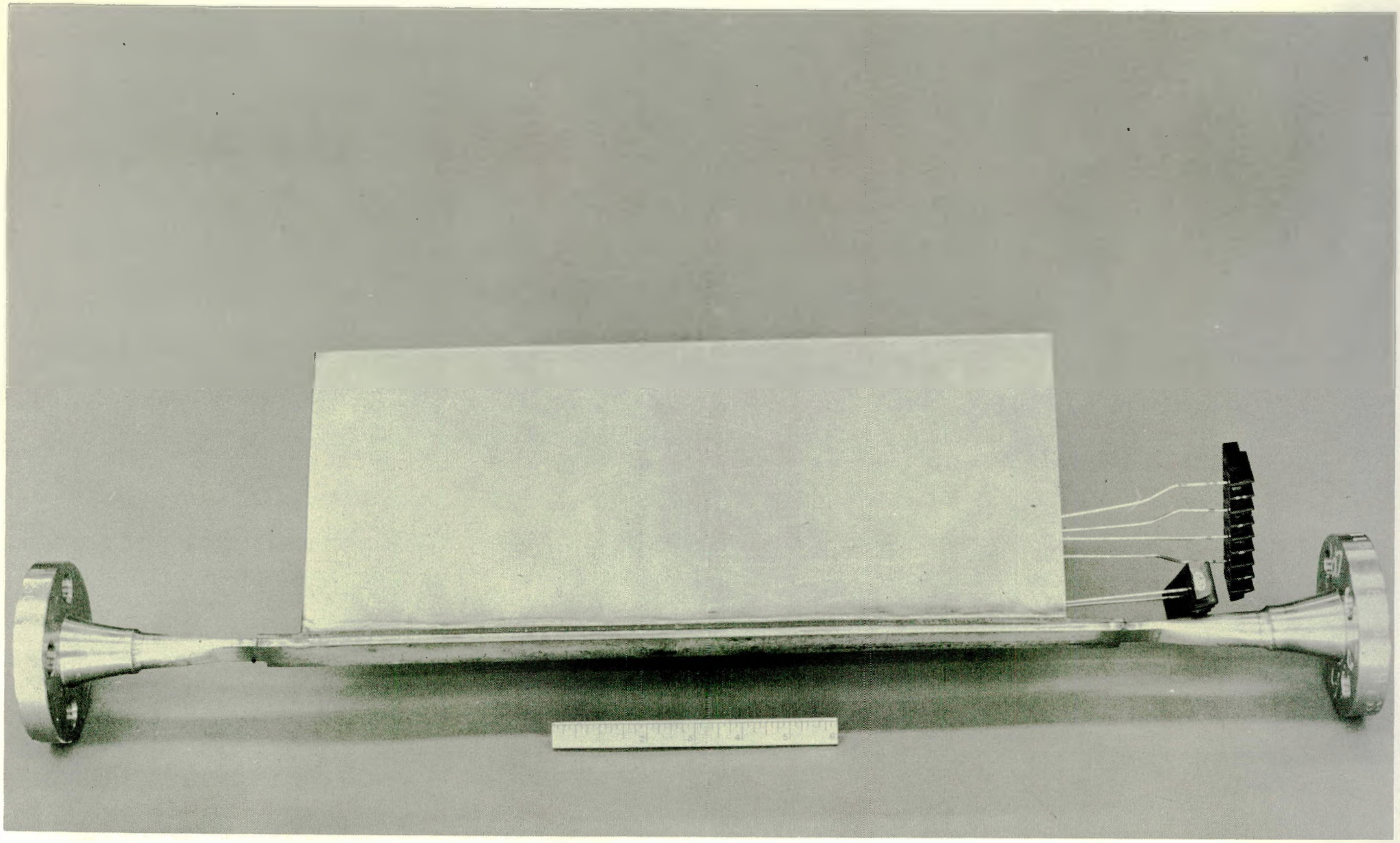


Fig. 33. Test Assembly Used to Compare Thermocouple Attachments in an Organic Thermal Loop

fuel plate mock-ups into a long narrow box. The thermocouples to be tested were attached to one of the plates. Flanges on each end of the simulated fuel box channel enabled the apparatus to be placed in an organic thermal loop. The plate to which the thermocouples were attached was heated by a molten lead bath contained in a long narrow tank welded to the fuel plate. The thermocouple attachments under test were fastened as shown in Fig. 34 to 30-mil-thick stainless-steel plate that simulated the fuel plate. A reference thermocouple was fastened to the surface of the plate by passing it through the plate from the other side. In this manner, the leads of the reference couple were not exposed to the coolant stream. The fuel plate mock-up was heated by the molten lead.

D. TEST RESULTS

The test results were interpreted by comparing the temperature measured at the thermocouple junction with the Reynolds Number of the hot coolant. Temperatures were measured at three places: (1) at the quartz-encased leads, (2) at the thermocouple junction in the copper disk, and (3) at a junction imbedded in the mock-up fuel plate (for measurement of the actual plate surface temperature). It was noted that as the Reynolds Number of the coolant is increased, temperature (1) and (2) both deviate from the actual surface temperature (3). At relatively low flow rates, the deviation between the two couples being tested is large but decreases as the flow rate is increased. At a value of 50,000, the Reynolds Number anticipated during reactor operation, the difference in readings between the two thermocouples is quite small. The test indicated that the thermocouple junction embedded in the copper disk indicates a value nearer the actual surface temperature than does the quartz covered couple. However, since either type of thermocouple attachment would have to be calibrated in either event in order to be useful, the attachment method using the quartz covered leads was chosen because of its simplicity and ease of attachment. Also, there was some question of the effect of the copper disk on the thermal neutron flux at the thermocouple junction.

E. THERMOCOUPLE CALIBRATION

The thermocouple attachment was calibrated by using a fuel plate heated by passing an electric current through the plate. This method closely approximated

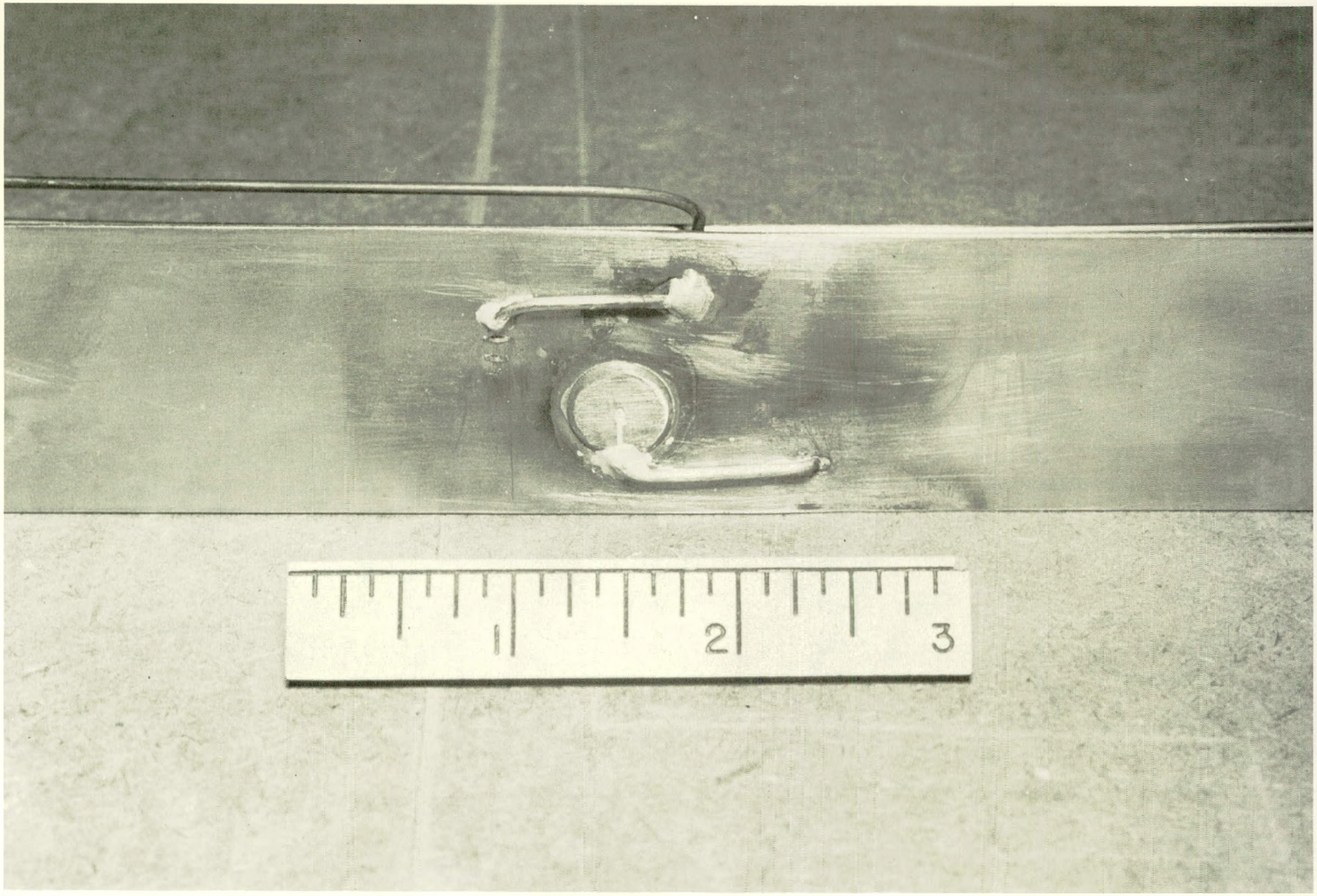


Fig. 34. Thermocouple Test Plate Showing Two Methods of Thermocouple Attachment to Fuel Plate

actual reactor conditions. Reference thermocouples were embedded in the fuel core. The assembly with the couples being calibrated was placed in a polyphenyl thermal loop. Results were comparable to the lead bath method.

IX. SUMMARY

After conducting a detailed investigation into the many variables encountered in the fabrication of OMRE fuel elements, the first core loading plus sufficient spare elements for one year's operation were completed. The elements were produced from thin, flat plates containing a stainless steel-UO_2 core clad with stainless steel. The fuel plates were retained in a stainless-steel fuel box by mechanical means. The program was completed within the scheduled time allotted and with a minimum of scrap. The over-all production losses were well below expectations as outlined in the Feasibility Report submitted to the Atomic Energy Commission office at San Francisco.

A program to evaluate these elements after irradiation should start early in 1958.

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