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Metallurgy Division

SPECIFICATIONS AND FABRICATION PROCEDURES

For

APPR-1 CORE II STATIONARY FUEL ELEMENTS

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Contract No. W-7405-eng-26

and

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Contract No. AT (30-3)-278

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DISCLAIMER

FORWARD

This report was prepared specifically to aid the Army Reactors Branch of the Division of Reactor Development in procuring the stationary fuel elements for Core II of the APPR-1 from an industrial fuel element manufacturer. The specifications and fabrication procedures covered herein were prepared as a joint effort on the part of Alco Products, Incorporated, and the Oak Ridge National Laboratory. The work performed by Alco Products, Incorporated, has partially fulfilled the requirements of Amendment No. 2 to Contract AT (30-3)-278.

An unclassified meeting is scheduled to be held at ORNL on July 31, 1958, for the purpose of furnishing all prospective fabricators with additional and identical information.

ABSTRACT

Stainless steel-base fuel components of thin plate-type construction and containing a dispersion of enriched UO_2 have been successfully employed in powering the Army Package Power Reactor. This report is concerned with the stationary fuel component proposed for operation in the second core loading of the reactor. The component is designed for radioactive service in pressurized water at 450°F and consists of eighteen composite fuel plates joined into an integral unit or assembly by brazing. Design specifications covering the material and dimensional requirements as well as the operating conditions are discussed. Step-by-step procedures developed and utilized in manufacturing the component are presented in detail.

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952 004

LIST OF FIGURES

Figure | Page

CONTENTS

352 007

SPECIFICATIONS AND FABRICATION PROCEDURES FOR APPR-1
CORE II STATIONARY FUEL ELEMENTS

I. INTRODUCTION

In order to continue successful operation, the Army Package Power Reactor at Fort Belvoir, Virginia, will require a replacement loading of fuel elements in the Spring of 1959. This report describes the specifications and fabrication procedures developed and adopted for the Core II stationary fuel elements. The information is presented in sufficient detail to enable an industrial manufacturer to undertake the task of furnishing a core-loading of stationary fuel elements with only a minimum of development effort. Specifications on the control rod fuel element and absorber section, which constitute an important segment of the active core, are not covered in this report. These components will be procured under separate contract.

The Army Package Power Reactor was built and placed into operation on April 12, 1957, to demonstrate the feasibility of exploiting the compactness of nuclear energy to supply heat and power at remote locations. The plant, designated as APPR-1, has a rated thermal capacity of 10 Mw and delivers to 2 Mw of electrical power at the turbo generator. The reactor is a pressurized-water-cooled and -moderated unit powered with highly enriched fuel. The fuel is loaded into the reactor core in the form of uranium dioxide dispersed in stainless steel.

The utilization of stainless steel-uranium dioxide fuel components for powering the APPR-1 was the culmination of a five-year-program effort of general materials and component development work at the Oak Ridge National Laboratory. The program was motivated by the limitations of aluminum and zirconium and by the advantages offered by stainless steel with its excellent corrosion resistance, its attractive physical and mechanical properties, and its amenability to simple and inexpensive fabrication practice.

II. DESCRIPTION OF COMPONENT

The basic segment of the stationary fuel element designed for radioactive service in APPR-1 is illustrated in Fig. 1. It consists of eighteen composite fuel plates joined by brazing into a pair of side plates to form an integral assembly. The flat rectangular fuel plate is composed of a

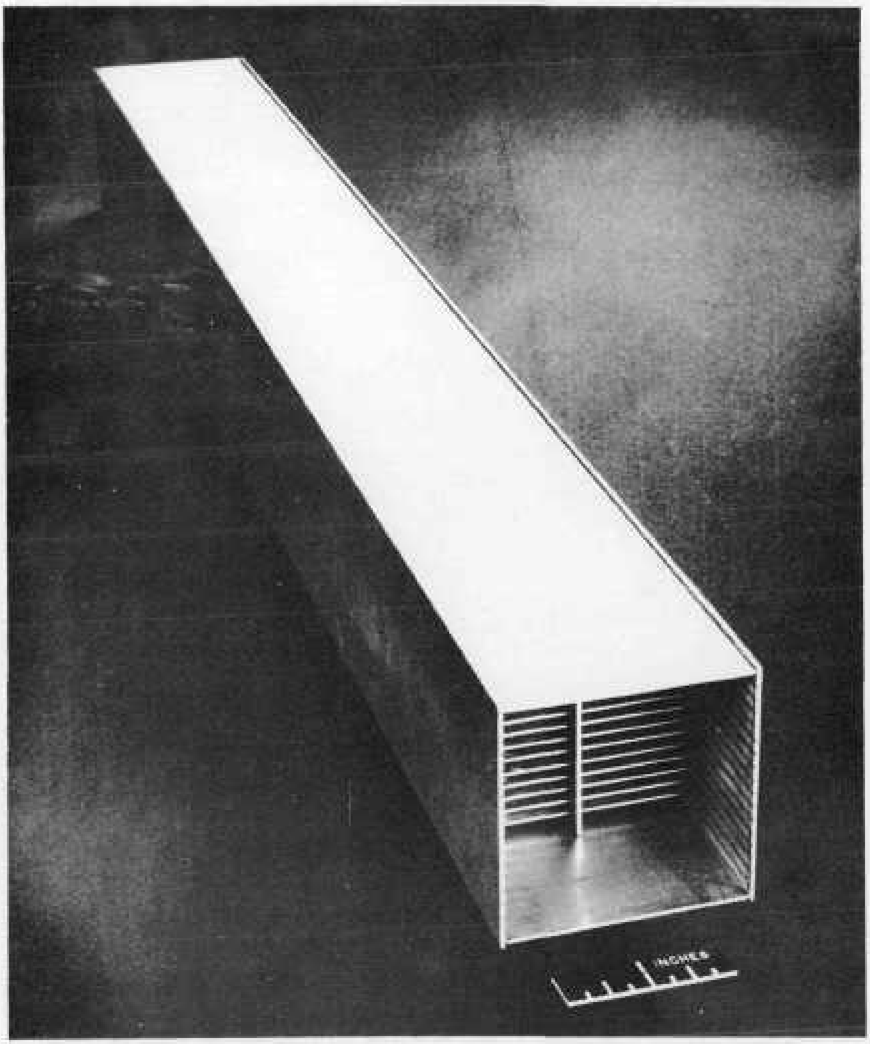

Fig. 1 (Y-24067) Brazed Stainless Steel Fuel Assembly Containing Eighteen Flat Composite Stainless Steel Fuel Plates.

0.020-in.-thick core section containing enriched UO_2 and a small quantity of B_4C uniformly dispersed in a matrix of stainless steel powder and a thin encasement jacket of wrought stainless steel. A representative cross section of a composite fuel plate with 0.005-in.-thick cladding is shown in Fig. 2. These composites are prepared by roll-bonding to promote heat transfer across the clad-core interface and to hermetically seal the fuel and resultant fission products from the coolant.

Each component contains approximately 515 g of uranium-235 and 0.5 g of boron-10. Boron is added to aid in controlling the excess reactivity of the heavily loaded core at start-up, and indirectly permits continuous operation of the reactor at full power output for a period of fifteen months without refueling. The unit is equipped with cast-type 304 stainless steel end boxes attached to the side plates by tungsten inert-gas welding. The purpose of the end fitting is to adapt the unit to the supporting grids which fix the position of the element in the reactor core. A spring is provided on the upper casting to allow for thermal expansion. An over-all view of the finished component with end adapters attached is illustrated in Fig. 3.

III. GENERAL REQUIREMENTS

A. The fuel component is designed for radioactive service in pressurized water and once placed in operation cannot be subjected to maintenance, repair, or salvage. It is imperative, therefore, that only the highest degree of quality obtainable with respect to materials of construction and workmanship be incorporated into the finished component. In addition, the product is intended for service in an existing system and cannot be altered. Hence, the component must be manufactured in strict accordance with the specifications and fabrication procedures set forth in this report.

B. Satisfactory performance of the reactor and of the fuel components during their operating life requires that special precautions be taken to insure the following:

1. A continuous metallurgical bond between clad and core matrix material must be obtained to insure proper heat removal and freedom from potential blisters which may rupture and release fission products to the coolant.

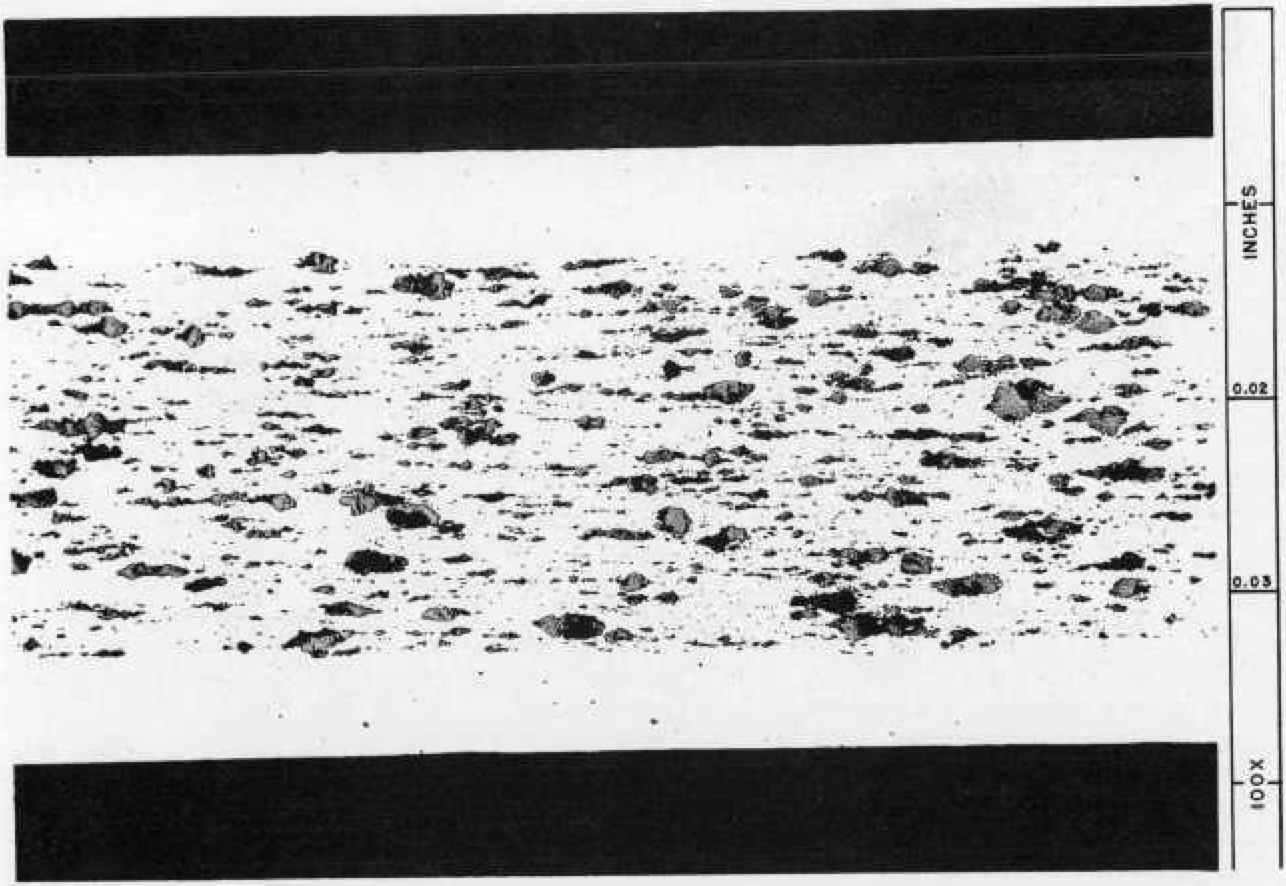

Fig. 2 (Y-25961) Cross Section of an APPR Composite Fuel Plate.

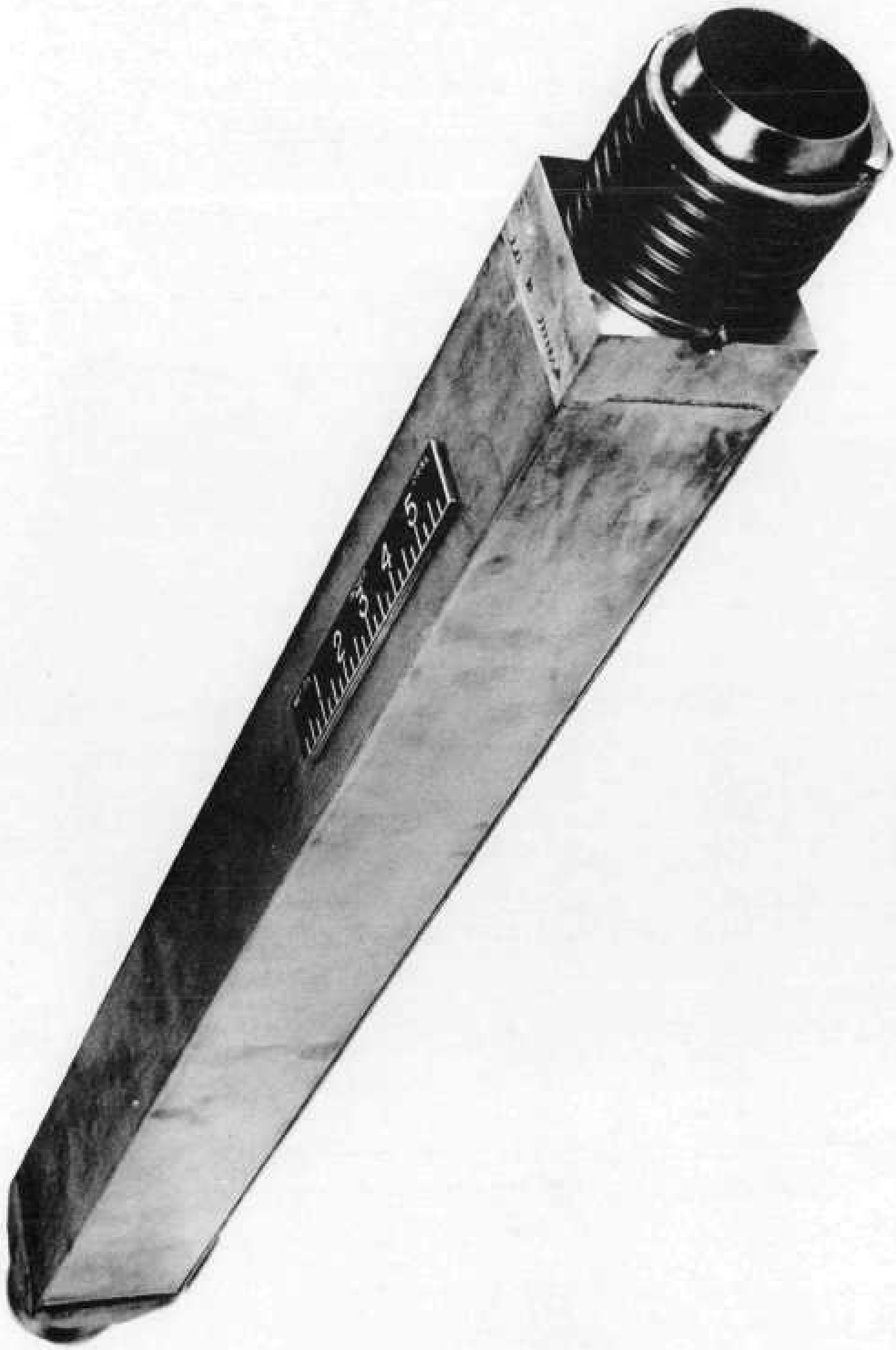

Fig. 3 (Y-19729) Over-All View of Finished APPR Fuel Element.

2. Uniform distribution of the fuel and burnable poison in the core of the composite plate must be achieved. Inhomogeneity of these important ingredients could lead to hot-spots and ultimate failure by melting.

3. Uniformity in thickness of clad and core material must be maintained to insure protection from corrosion by the coolant and to achieve the required concentration of fuel in terms of grams of U-235/cm^2 over the entire area of the active portion of the fuel plate.

4. The composition and processing of materials must be controlled to minimize the presence of contaminants which may (a) accelerate corrosion, (b) contribute to parasitic absorption of neutrons, (c) reduce mechanical integrity of the fuel elements, (d) release gases which could promote swelling or blistering and ultimate rupture of the cladding, or (e) contaminate the surfaces of the fuel elements with traces of fissionable or fertile material that would increase the level of radioactivity in the coolant.

5. The various steps of framing, cladding, shearing, machining and brazing must be carried out and inspected in a manner to preclude the presence of fissionable material at the clad-frame interface as well as to insure that no portion of the fuel-bearing core is exposed to the coolant.

C. Experience in the manufacture of the first core loading for the APPR-1 and similar fuel elements has demonstrated the feasibility of fabricating components which consistently meet the product standards required. Substantial assurance that the component meets these standards cannot be accomplished exclusively by nondestructive testing of random or control samples. Instead, these must be combined with the establishment of and rigid adherence to proven fabrication procedures, materials inspection and cleanliness standards. Industrial utilization of the detailed processing procedures presented in Section V (Manufacturing Procedures) does not relieve a manufacturer from any responsibility associated with the fabrication of a satisfactory product for service in Core II of the APPR-1.

D. Sufficient and proper supervisory and production control must be provided by a manufacturer: 1) to insure that all details of the fabrication procedure conform at all times with the approved procedure, 2) to maintain rigid adherence to all specification requirements, 3) to protect personnel against human intake of airborne activity from alpha-emitting UO_2 by inhalation or ingestion and to comply with the requirements of the International Commission on Radiation Protection, 4) to enforce safety measures to prevent a criticality incident, and 5) to safeguard and account for all fissionable material in accordance with the Atomic Energy Commission licensing agreement, or other arrangements with the AEC, as defined under the Atomic Energy Act.

E. It will be necessary to maintain sufficient and proper records to supply complete metallurgical history, fuel accountability, inspection, quality control, and other pertinent data required in the fabrication of the fuel elements.

F. In addition to the identification numbers specified in the fabrication procedure for components and fuel elements, a symbol indicative of the manufacturer shall be added to the end boxes on each fuel element.

IV. DESIGN CRITERIA

A. Basic Requirements

The design of the stationary fuel element for service in Core II in the APPR-1 is based on the following criteria: 1) operation at a high specific power density and reduction of core volume by utilizing enriched fuel, 2) extension of reactivity lifetime by utilizing a burnable poison, 3) dispersion of the fuel and burnable poison in a suitable diluent to maximize heat transfer, 4) cladding of the fuel-bearing section for corrosion protection and retention of fission products, 5) utilization of inexpensive materials of construction and low-cost methods of processing to minimize fuel cycle costs, and 6) employment of a metal-to-metal bond and thin plate-type construction to promote efficient heat removal.

The active core of the APPR-1 is composed of thirty-eight stationary fuel components and seven movable control rod assemblies immersed in water. The water serves as moderator, reflector, and heat-transfer media. The system is pressurized to 1200 psia and water flows through the channels between adjacent fuel plates at an average velocity of 4.3 fps.

The stationary fuel component consists of eighteen flat composite plates joined to a pair of side plates by brazing to form an integral assembly with a nominal water-gap spacing of 0.133 in. ± 0.013 in. A line drawing with dimensional requirements of the component is given in Fig. 4. This drawing is for reference only and should not be used for fabrication.

Other pertinent design and operating data are listed in Table I. The data given for make-up of the fuel-bearing section of each composite plate are for information only and are based on utilizing materials of the following specifications: 1) UO_2 with a total uranium content of 87.63 wt % and a uranium-235 isotopic enrichment of 93.07 wt %, and 2) B_4C containing a total boron content of 75.90 wt % and boron-10 isotopic concentration of 18.09 wt %.

B. Material Selection

1. Introduction - In general, alloys of uranium with stainless steel or with any of the elemental constituents of stainless steel cannot be considered as fuel materials because of the presence of low-melting eutectics and brittle intermetallic compounds. Therefore, the development of stainless steel fuel elements has centered on the selection of a uranium-bearing compound which is metallurgically compatible and chemically inert when dispersed in stainless steel and processed at elevated temperatures.

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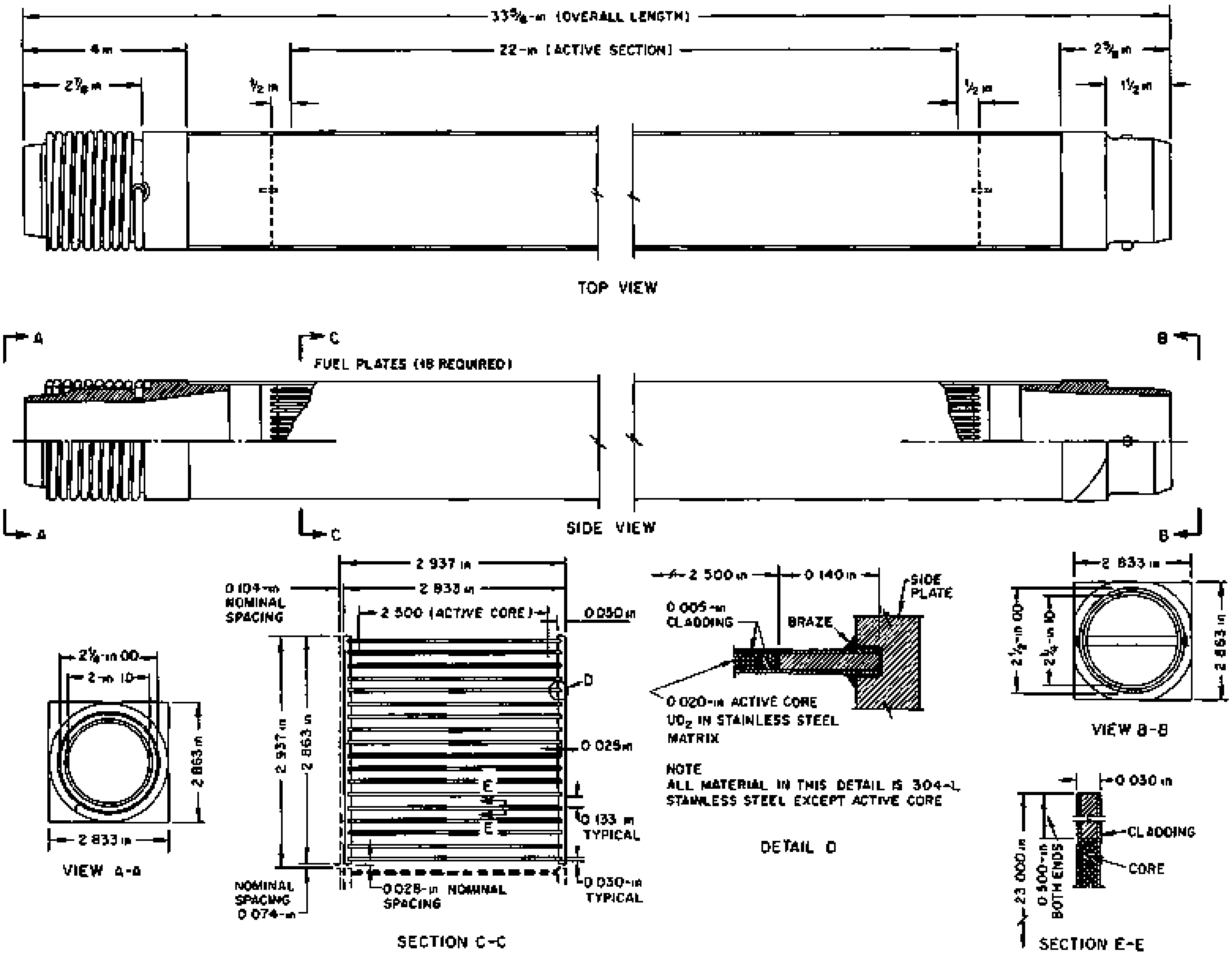

Fig. 4 Dimensional Drawing of APPR Fuel Element.

TABLE I

DESIGN DATA ON APPR FUEL COMPONENT

General Description

Number of Fuel-Bearing Plates per Assembly	18
Fuel Plate Clad-Core-Clad Thickness, mil	5-20-5
Water Gap Spacing, mil	133
Boron-10 Content per Assembly, g	0.464
Uranium-235 Content per Assembly, g	515.16
Metal-to-Water Ratio	0.25

Materials Make-Up Data

Fuel Core Composition per Plate	g	Wt %	Vol %
UO_2 (44-88 μ particle size)	35.09	25.032	19.43
B_4C (< 44 μ in size)	0.188	0.134	0.45
304B Stainless Steel (< 149 μ size)	104.90	74.834	80.12
Fuel Density per Plate, g/cm^2	0.079 min	-	0.085 max

Operating Data at 10 Mw Thermal Output

Power Density, kw/liter	71.7
Average Heat Flux, $BTU/hr\text{-}ft^2$	55,900
Bulk Water Outlet Temperature, °F	450
Pressure in Reactor Core, psia	1200
Average Velocity in Water-Gap Spacing, fps	4.3
Average Thermal Neutron Flux, n/cm^2-sec	1.5×10^{13}
Expected Reactivity Lifetime, Mwy	13
Estimated Average Burn-up, % total atoms	1.6

2. Uranium Dioxide - The refractory compound UO_2 with its excellent high-temperature properties meets these general requirements. The compound is chemically inert in contact with stainless steel at temperatures as high as 2550°F and exhibits good resistance to corrosion in pressurized water. Furthermore, it can be produced in an economical manner and has a relatively high content of fuel as compared to most uranium-bearing compounds. Uranium dioxide is relatively insensitive to radiation damage and does not undergo deformation at low temperatures as uranium metal does when subjected to reactor-induced radiation. Uranium dioxide also offers the advantage of good fission-gas retention primarily attributed to its defective lattice structure. The chief disadvantages of low thermal conductivity and brittleness, which are characteristic of UO_2, are largely overcome by the nature of the dispersion-type fuel component.

The UO_2 is prepared by the thermal decomposition of $UO_3 \cdot H_2O$ in a hydrogen atmosphere. This oxide, generally known as "Geneva type" oxide, was originally prepared in quantity at the Y-12 Plant of Union Carbide Nuclear Company. A particle size range of 44 - 88 μ is used to minimize fission-fragment damage to the stainless steel matrix.

3. Boron Carbide - Boron-10 was selected as the burnable poison because its nuclear burnout characteristics closely match those of the fuel. It is added as natural boron in the form of boron carbide (B_4C).

4. Austenitic Stainless Steel - Austenitic stainless steel, type 304L, was selected as the cladding and structural material for APPR-1 fuel components. This material is relatively cheap, readily available in the desired forms, and amenable to most mechanical-working and welding operations. It has excellent corrosion resistance in high-temperature water and adequate strength and ductility to withstand the thermal stresses and gradients encountered in operation. The alloy has fair heat-transfer properties, and is not subject to serious structural damage under irradiation. On the other hand, stainless steel would impose a severe nuclear penalty if substituted for zirconium on a volume-to-volume basis. This penalty can be partly overcome by judicious design utilizing the full potential of the high-strength properties of the alloy. Care must also

be taken to use a steel with low-cobalt content in order to minimize the radio-chemical transport problem associated with high-activity cobalt-60 which enters the primary-loop system as a corrosion product.

5. Brazing Alloy - Coast Metals N. P. brazing alloy is specified as the brazing alloy. This alloy contains a nominal composition of 50 wt % Ni - 27 wt % Fe - 11 wt % Si - 8 wt % Mo - 4 wt % P and flows at 2066°F.

6. End Boxes - End boxes may be used in the fuel elements in the as-cast condition as either sand-cast or precision-cast type 304L stainless steel with a maximum cobalt content of 0.01%. Lebanon Steel Foundry, Lebanon, Pennsylvania and Arwood Precision Castings Corporation, New York, N. Y., have indicated interest in supplying end boxes of this composition.

V. STATIONARY FUEL ELEMENT SPECIFICATIONS

A. Core Material Requirements

1. Fuel

U-235 per plate, g		28.62
Enrichment, %		93 ± 1
	Allowable tolerances*	
Weighing		±0.03%
Enrichment		±0.10%
U_T/UO_2		±0.25%
Handling loss		-0.19%

2. Burnable Poison

B-10 per plate, g		0.02581
	Allowable tolerances*	
	Weighing	±0.30%
	B_N/B_4C	±1.00%
	Losses in sintering	-7.00%
	Handling loss	-0.20

*Allowable tolerances were established by ORNL as a result of evaluation of the uncertainties involved in fabricating Core I.

3. Composition of Fuel-Bearing Core - The fuel, burnable poison, and matrix requirements per plate are as follows:

28.62 g of U-235

0.02581 g of B-10

104.9 g of type 304B stainless steel powder

The weight of matrix material per plate is subject to the requirements specified in Section VI-C.

B. Material Specifications

1. Fuel - The fuel shall be UO_2 powder prepared by the "Geneva" process, and shall be procured from the Y-12 Production Plant at Oak Ridge, Tennessee. The UO_2 shall contain approximately 88 wt % total uranium and have a U-235 isotopic concentration of 93% ± 1%. Particle size shall be 44 – 88 μ. The UO_2 shall be free of agglomerates, platelets, rods, and clinging surface fines.

"Geneva" process product is prepared by growing hydrothermally UO_3 hydrate crystals from a UO_4 hydrate -10% uranyl nitrate aqueous solution in an autoclave at 250°C for 10 hr. After thorough rinsing to remove all traces of nitrate, the UO_3 hydrate crystals are fired at 1750°C under a hydrogen atmosphere for reduction to UO_2. The material is screened for 44 – 88-μ size recovery.

2. Burnable Poison - The burnable poison material shall be natural B_4C powder equivalent to that supplied by Norton Chemical Company as High Purity Grade containing approximately 76% natural boron. Particle size shall be less than 44 μ.

3. Matrix Material - The matrix material shall be type 304B stainless steel powder with maximum carbon content of 0.03 wt % and a silicon content of approximately 2.5 wt %. The powder shall be equivalent to that supplied by Vanadium Alloys Steel Company. Particles shall be of irregular shape and less than 149 μ in size.

4. Wrought Stainless Steel - A special grade of low-cobalt type 304L wrought stainless steel shall be used as the clad and frame material in the fuel plates as well as for the side plates and combs of the fuel element. This material will be made available. Typical analyses of this heat of steel is listed below:

Element	Wt %
C	0.018
Mn	1.72
P	0.010
S	0.020
Cr	18.70
Ni	9.57
Co	0.004/0.005
Al	0.062
Mo	0.0097
Cu	0.10
N_2	0.05
Pb	0.001
Ta	0.001
Sn	0.009

5. Brazing Alloy - The brazing material shall be Coast Metals, N.P. powder of less than 88-μ size, and can be obtained from Coast Metals, Incorporated, Little Ferry, New Jersey. This material shall be free of boron.

6. End Boxes - End Boxes shall be castings of 304L composition with 0.01% maximum cobalt content. Surface finish requirements shall be 125 RMS.

7. Other Materials - Care must be exercised in utilizing the other materials, such as electrodes, filler rod, cleaning agents. and lubricants that come into contact with the product during processing. All lubricants, for instance, shall be of non-halogen-bearing type. Pickling of the fuel plates in any solution containing a halide ion or reducing in nature shall not be allowed subsequent to removal of scale from the hot-rolled fuel plates. The use of any processing agent that may have a deleterious effect on the finished product is prohibited.

C. Dimensional Requirements

The component parts shall be manufactured in accordance with the dimensional specifications set forth on Alco Drawings listed in Section VIII.

D. Finish Requirements

All machined surfaces in contact with the coolant shall have a finish of at least 125 RMS except where noted on the drawings. Rolled surfaces shall have a surface finish of at least 50 RMS.

E. Qualification of Fabrication Procedure

1. Introduction - Quality control of the fuel elements is primarily attained by rigid adherence to proven fabrication procedures. Thus, specifications for the stationary fuel elements cannot be prepared along the lines normally used for industrial products, in which quality is assured by non-destructive inspection to industry-wide standards. Consequently, the fuel element manufacturer will be required to qualify the fabrication procedure which is to be employed in the fabrication of the stationary fuel elements.

2. Method of Qualification - Qualification shall be performed by subjecting six sample fuel plates to the tests outlined in 4-a - 4-i of this section. Approval of qualification shall be given by the Contracting Agency or its authorized representative when it has been demonstrated to the satisfaction of the Contracting Agency or its authorized representative that the requirements of 4-a - 4-i have been met.

3. Preparation of Qualification Samples - The six sample fuel plates shall be prepared in conformance with the exact and complete fabrication procedure which is proposed to be used in the manufacture of the stationary fuel elements. Depleted uranium oxide, identical in every respect with the material to be used in the stationary fuel elements except in enrichment,

shall be used in the sample fuel plates. The sample fuel plates shall be subjected to the maximum number of exactly duplicated high-temperature treatments which will be encountered in the proposed procedure for fabrication of completed fuel elements. Approval of qualification must be obtained prior to inception of manufacture of enriched fuel plates unless otherwise specifically authorized by the Contracting Agency or its authorized representative. Approval by the Contracting Agency or its authorized representative of the procedure as used in establishing qualification or of any modification thereof will not relieve the manufacturer of any responsibility for any phase of the fabrication of the stationary fuel elements or for conformity to specification requirements.

4. Tests for Qualification -

a. Visual Inspection

The six sample fuel plates shall be inspected for over-all width, length, and thickness dimensions and shall be inspected for pitting, surface condition, and finish. The six sample fuel plates shall meet all dimensional requirements and shall not exhibit any oxide indentations or pits over 0.001 in. deep, scratches over 0.001 in. deep, dents over the core area, blisters, scale, or discreet color changes over the core area.

b. X-Ray Examination

The six sample fuel plates shall then be x-rayed to delineate the fuel-bearing core area and to reveal any fuel segregation and voids or other internal defects. The radiographs shall be made using proper techniques with a fine-grained film such as Eastman "M", exposed and processed to yield a gamma density of 1.0 - 1.25 over the core area. The radiographs shall be used as the basis of measuring core length, core width, and inactive edges and ends.

The samples shall meet all dimensional requirements and shall exhibit no evidence of fuel segregation, voids or other internal defects.

c. Surface Contamination

The six sample fuel plates shall be subjected to a smear test on both sides of the fuel plates. Alpha counting of the absorbing material shall exhibit no evidence of contamination by fissionable material.

d. Clad Sensitization and Intergranular Attack

Some increase in carbon content of the clad material must be expected due to diffusion of carbon from the core material during the various high-temperature treatments to which the fuel plates are subjected. Experience has proven that the relatively small increase in carbon content of the clad material causes no deleterious effect during reactor operation. However, it is mandatory that no additional carbon from external sources contaminate the cladding.

The degree of external carbon contamination can be evaluated by testing samples from the inactive portion of the composite fuel plate. Two transverse specimens of the full-plate width shall be taken (one at each end) from each of the six sample fuel plates and subjected to the Strauss Test. The samples shall not exhibit any evidence of cracking after bending 180 deg around a 1/8-in.-dia mandrel nor evidence of serious intergranular attack when examined metallographically at 100X in the as-polished condition.

e. Homogeneity

If the six sample fuel plates exhibit satisfactory homogeneity as evidenced by examination of the x-ray films, two of the six shall be further examined. Five miniature samples of full-plate thickness, approximately one square inch in area, shall be extracted from each of the two fuel plates on a diagonal between core corners and approximately equally spaced. These samples shall be chemically analyzed for total uranium and boron contents, and the results expressed on a weight per cent basis. For each of the two plates, variation from location to location shall not exceed one-half per cent of the uranium content and 20% of the boron content.

f. Bond Integrity

Five transverse samples equally spaced along the plate length and three longitudinal samples from each end equally spaced across the width shall be removed from two of the six sample fuel plates. After proper preparation and electrolytic etching with 5% chromic acid reagent, the samples shall show no evidence of lack of bond at the clad-frame interface or at the clad-core interface upon metallographic examination at 100 diameters.

g. Clad-Core-Clad Thickness

The ten transverse samples used in "f" shall be metallographically measured to determine clad-core-clad thickness. As measured by filar micrometer, all of the thickness at all points in the samples shall show compliance with specified thicknesses.

h. End Conditions

The twelve longitudinal samples used in "f" shall be examined metallographically. These samples shall show no evidence of the presence of core material in the inactive portions as dimensionally specified or of the presence of voids at the core-frame interface.

i. Fuel Fragmentation and Stringering

One longitudinal sample at least one-half inch long shall be taken from the core of each of four sample fuel plates. When examined metallographically, none of these samples shall exhibit fragmentation and stringering greater than that illustrated in Fig. 5.

5. Conformance of Fabrication Procedure - The exact procedure used in fabricating the sample fuel plates and which is proposed to be used in fabricating the active fuel plates shall be furnished to the Contracting Agency or its authorized representative at the conclusion of fabrication of qualification plates and at least one week in advance of the request for approval of qualification. Unless otherwise specifically authorized in writing by the Contracting Agency or its authorized representative, the procedure used in fabricating the sample fuel plates shall be strictly adhered to in fabricating the fuel plates and the stationary fuel elements.

6. Liaison and Inspection - Free entry shall be given to the Contracting Agency or its authorized representative to all areas of the manufacturer's plant at any time during the term of the contract for fabricating the stationary fuel elements. The manufacturer shall provide

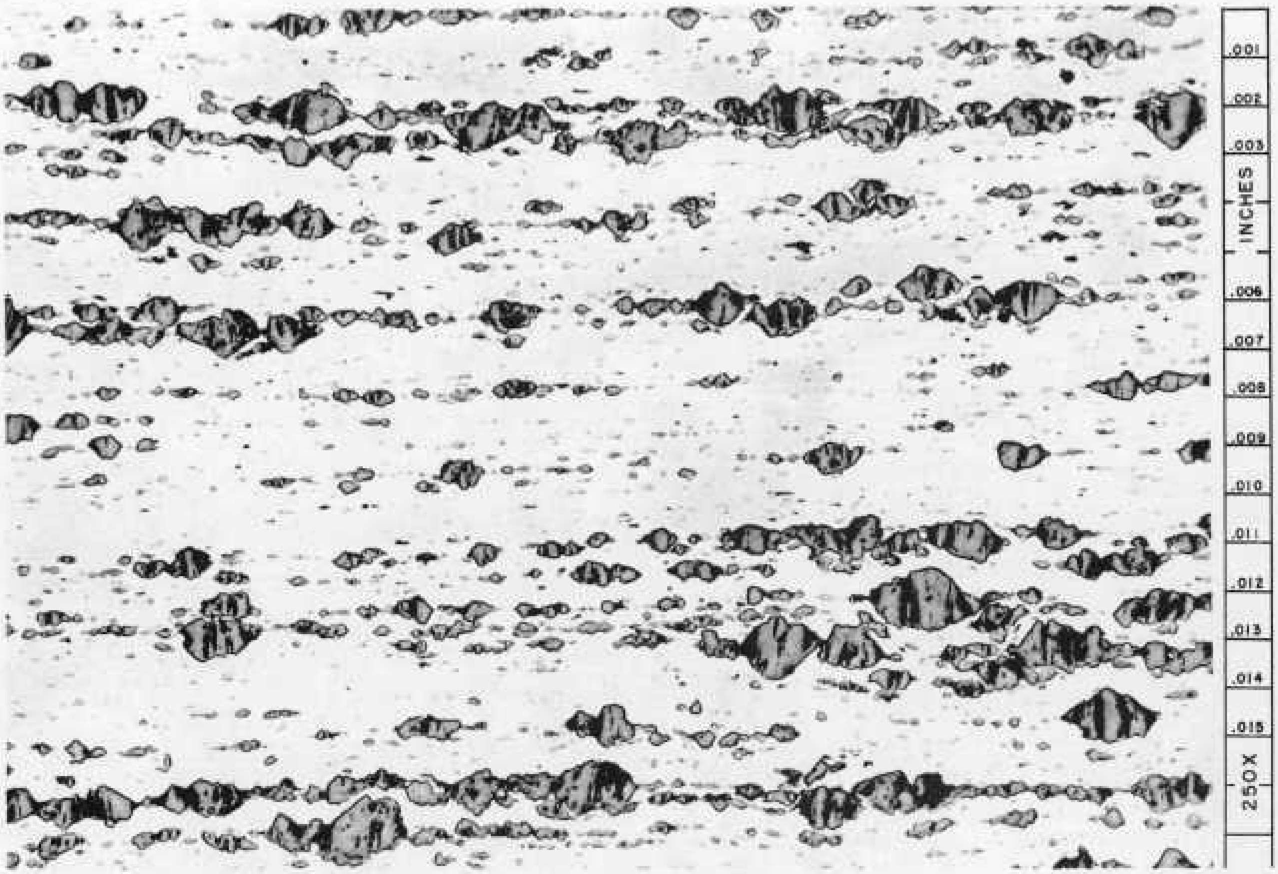

Fig. 5 (Y-18927) Typical Stringering and Fragmentation of UO_2 in Stainless Steel Matrix of Cold-Rolled Fuel Plate.

all reasonable assistance, facilities, and cooperation to the Contracting Agency or its authorized representative for determination of compliance with specification or procedure requirements or for inspection purposes as may be required.

The Contracting Agency or its authorized representative will maintain liaison with the manufacturer for the duration of the contract for the following purposes: 1) to provide necessary and reasonable technical assistance as may be required; 2) to inspect for compliance to the specifications and the approved fabrication procedure. The Contracting Agency or its authorized representative shall have the right at any time during the term of the contract to reject any and all pieces, parts, components, and products which do not meet the requirements of the specifications, or which have not been fabricated in accordance with the approved procedure, or which fail in any way to meet any of the requirements set forth in this document. Such inspection shall not relieve the manufacturer of any responsibility in any phase of fuel element fabrication or furnishing thereof.

7. Certification - Certification shall be furnished to the Contracting Agency or its authorized representative that all materials used in the fabrication and furnishing of the fuel elements are in accordance with the requirements of these specifications.

VI. MANUFACTURING PROCEDURES

A. Introduction

The flow of material in processing stationary fuel elements for the APPR-1 is illustrated in the simplified diagram shown in Fig. 6. The essential operations required in processing are: 1) weighing of the component powder for each individual fuel core, 2) pressing, sintering, and coining into a compact of the required dimensions, 3) encapsulating the core within a welded billet, 4) cladding by roll bonding, 5) descaling of the hot-rolled plate, 6) cold rolling to specified final thickness, 7) marking and shearing of the composites, 8) machining to finished length and width dimensions, 9) flatten annealing, 10) assembling and brazing, 11) inspection of brazed fuel element, 12) attachment of end adapters, and 13) final machining. After machining, the elements are degreased and packaged for shipment to the reactor. These general procedures and the more specific details, which will be described later, represent methods developed and adopted by the Oak Ridge National Laboratory. It is recognized that because of differences in equipment, other fabricators may be required to modify some of the detailed procedures to arrive at the same result. However, the basic objective of each major step in the manufacturing process should be maintained.

Due to variations in equipment, procedure, or environment, it is usually prudent on the part of a potential fabricator to process test plates and components containing depleted or normal oxide before handling enriched material. Such test plates and components are then subjected to a rigorous inspection, involving both destructive and non-destructive testing methods, to determine whether or not changes in equipment or procedure are required to meet product standards.

B. Records

It is necessary to maintain complete identification during manufacturing process because of 1) accountability of the fissionable U-235 and burnable poison B-10, 2) segregation of rejected material, and 3) evaluation of the fabricated plates subsequent to manufacturing.

Records of the following items are maintained: 1) identification of each lot of UO_2 received from the UO_2 processing plant, 2) master log containing complete manufacturing data for each plate, and 3) fuel element inspection card of critical dimensions.

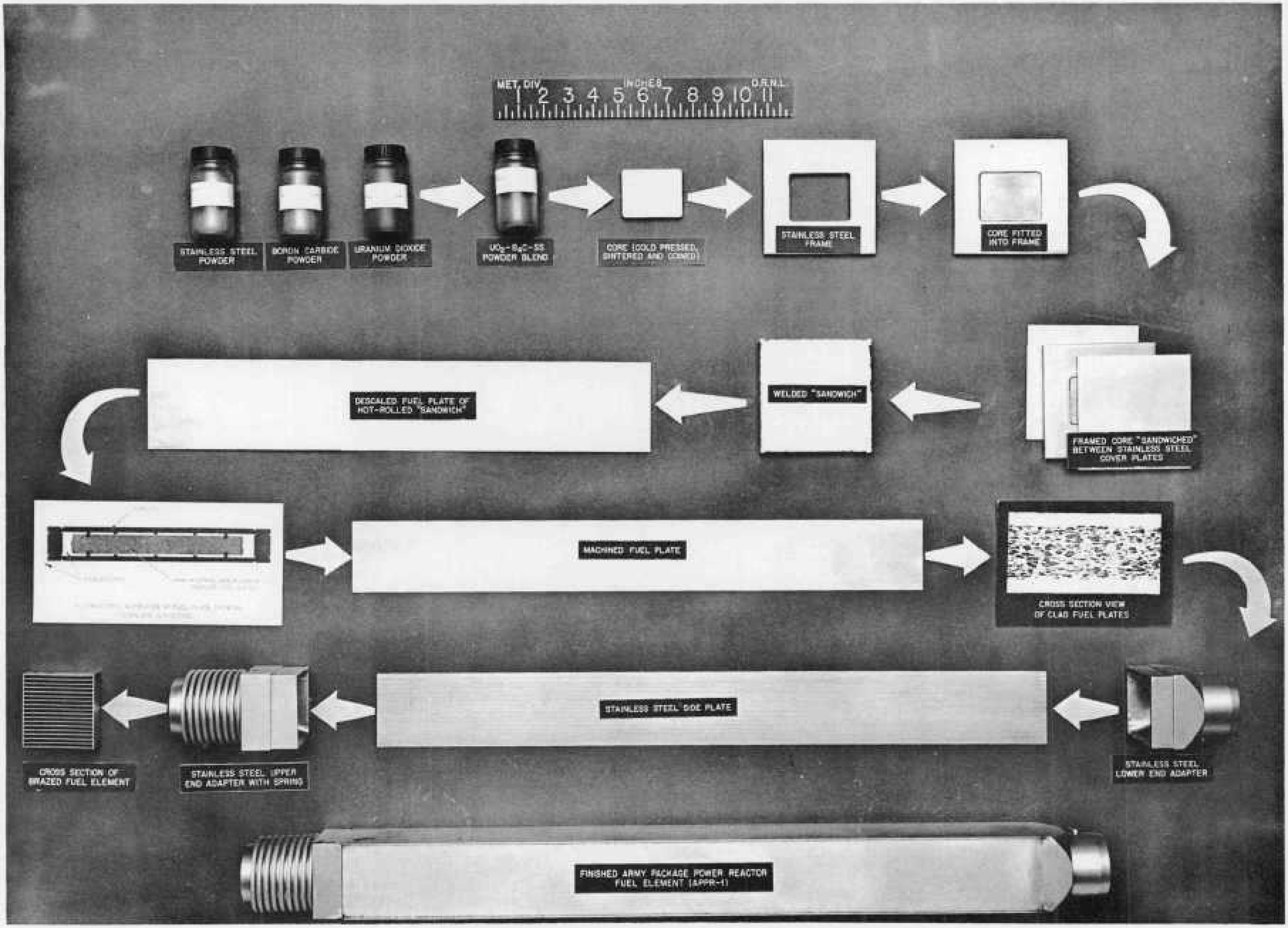

Fig. 6 (Y-25687) Fabricational Procedure for Manufacturing APPR Fuel Components.

C. Fuel Core Manufacture

1. Calculations - The fuel, burnable poison, and matrix powders are specified in terms of grams of uranium-235, boron-10, and stainless steel. Since the fuel is used in the form of UO_2 and the burnable poison in the form of natural B_4C, it is necessary to determine by calculation the quantities of these materials which are to be incorporated into each core. Each batch of as-received UO_2 is assayed for total uranium content as well as for isotopic concentration of uranium-235. Likewise, the concentration of boron in the boron carbide is accurately determined. Natural boron contains a constant 18.09 wt % of B-10, and, therefore, it is not necessary to analyze the boron carbide for isotopic concentration of boron-10.

Sample calculations illustrating the method utilized in determining the required quantities of UO_2 and B_4C in each fuel plate are listed below.

a. Data required:

wt % U-235 in U	93.07
wt % U in UO_2	87.63
wt % B-10 in B_N	18.09
wt % B in B_4C	75.9
g U-235 per plate	28.62
g of B-10 per plate	0.02581

b. Determination of grams of UO_2 per plate:

$$\text{Grams of } UO_2 = \frac{28.62 \text{ (g U-235)}}{\frac{87.63}{100} \text{ (wt \% U in } UO_2) \times \frac{93.07}{100} \text{ (wt \% U-235 in U)}} = 35.09$$

c. Determination of grams of B_4C per plate:

$$\text{Grams of } B_4C = \frac{0.02581 \text{ (g B-10)}}{\frac{75.9}{100} \text{ (wt \% B in } B_4C) \times \frac{18.09}{100} \text{ (wt \% B-10 in } B_N)} = 0.188$$

As might be expected, the final density or the densification factor $\left(\frac{\text{measured density}}{\text{theoretical density}}\right)$ of the as-fabricated core material has a significant effect on the charge of stainless steel powder required to meet dimensional specifications in the finished composite plate. This factor has been determined to be

0.93 for the specific equipment and processing methods employed at the Oak Ridge National Laboratory. However, any major change in equipment or procedure will probably shift this factor; and under such circumstances, it will be necessary to alter the grams of stainless steel required in the material charge for the fuel compact. Any proposed change in stainless steel content of the core for this or other reasons necessitates a corresponding change in the boron-10 requirements. This relationship is shown graphically in Fig. 7.

2. Weighing of Component Powders - The component powders for each individual core are separately weighed and combined in a single blending jar. With the exception of possible losses during subsequent pressing and sintering operations, this method offers accurate accounting of the critical ingredients, U-235 and B-10, in each fuel core within the limits of the accuracy of the weighing balance. Boron carbide is the first material loaded into the blending jar, and is followed by the stainless steel and finally the uranium dioxide. This sequence permits the boron carbide and stainless steel powders to be handled in a conventional manner, thus eliminating the inconvenience of weighing these materials within a dry box as is required during handling of finely divided UO_2. During processing, ten jars are handled as a unit operation and the individual weighing procedures are as follows:

a. Weighing of the Boron Carbide

The burnable poison in the form of B_4C is weighed to an accuracy of at least 0.3% on a Gram-matic balance of 200 g capacity. A 4 in. x 4 in. sheet of glazed paper with glazed side up and of known weight is placed on the pan. The burnable poison is added to the paper and accurately weighed. The material is then poured into a clean, wide-mouth, glass jar of 4-oz capacity. A camel's hair brush is used to brush any remaining particles of B_4C into the jar, which is then capped.

b. Weighing of the Stainless Steel Powder

The stainless steel is weighed in exactly the same manner as the burnable poison, with the exception that an analytical balance is used. The powder is weighed to a tolerance of ±0.01%. It is then transferred to a blending jar containing the previously weighed burnable poison. The jar is immediately recapped.

GRAMS OF B-10 REQUIRED FOR VARYING STAINLESS STEEL MATRIX
U-235 LOADING = 28.62 GRAMS PER PLATE

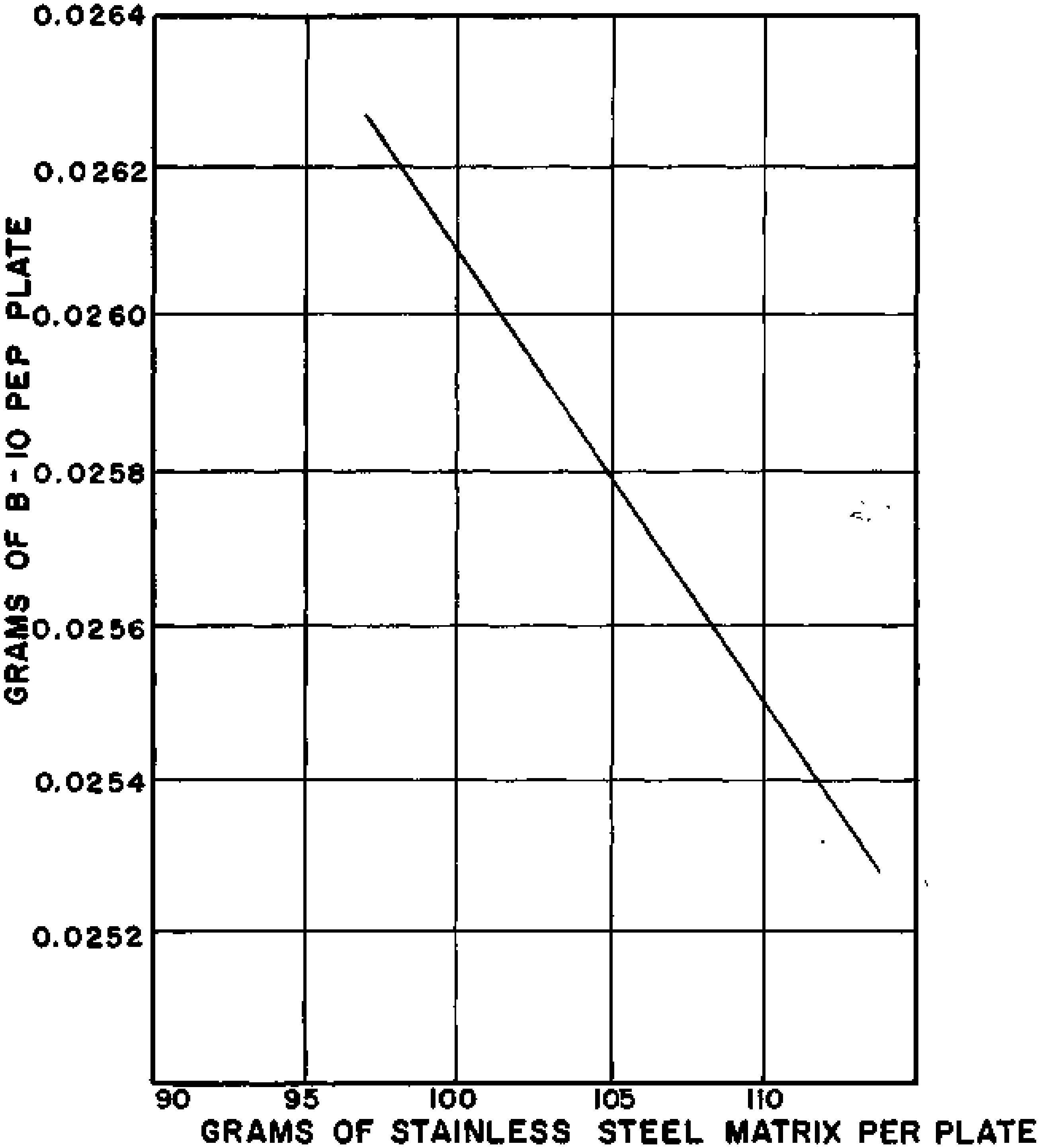

Fig. 7 Graph Showing Grams of B-10 Required for Varying Stainless Steel Matrix.

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c. Weighing of UO_2

Weighing of the fissile compound is accomplished within a protective box in which the atmosphere is under a slight negative pressure. The equipment is illustrated in Fig. 8. Gloves are attached to the ports shown and the hood connected to an exhaust system. The side port permits access to the interior, and the dry box is designed to accommodate a batch of ten jars or more. The box is equipped with a triple-beam balance of 100 g capacity, on which the UO_2 can be weighed with an accuracy of ±0.03%. The required quantity of UO_2 for one fuel core is weighed directly on the scale pan of the triple-beam balance using a scoopula for fine adjustment of fuel quantity. The specified weight of fuel is added to the jar containing the boron carbide and stainless steel powders. The jar is then capped and placed on the right or exit side.

These operations are repeated until the lot of ten jars has been filled, at which time they are withdrawn through the right side port. After removal from the dry box, the joint between the cap and the jar is sealed with masking tape. The UO_2 lot number is then marked on each jar, and they are placed in a transfer box for removal to the blending area. When the supply of UO_2 remaining in the dry box is insufficient for ten cores, it is set aside for later use in smaller lots.

3. Blending - The powders are blended in order to obtain a homogeneous mixture of fuel, poison, and matrix material. A modified U. S. Stoneware Company Double Cone Blender, Model 733, is used. The blender cones are replaced by a pair of two-quart steel cans mounted on the motor shaft at an angle of 30 deg with the vertical. Ten jars, each containing the specified quantities of UO_2, B_4C, and stainless steel, are loaded into each can with sufficient padding to prevent breakage of the jars during the blending operation. The cans are rotated at this oblique angle for two hours, after which the jars are removed and uncapped. Approximately 0.1 g (two squirts with a hand atomizer) of C. P. dodecyl or lauryl alcohol is added to each jar. The jars are recapped, resealed with masking tape, and blended for another hour.

4. Cold Pressing of the Core Ingredients - The first operation in shaping the blended powders into a compact suitable for assembling into a fuel plate billet is to cold press into a "green" compact. The press used is a 150

Fig. 8 (Y-13060) Dry Box Containing Equipment for Weighing Enriched UO_2 Powder.

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ton Baldwin press with a Vickers hydraulic control system which allows variable ram movement. The press has two rams, an upper fixed ram extending down from the top crosspiece and a lower ram which is movable. On the top of the lower movable ram is fastened a large platen, on which is placed the die set and dry box. The die set, illustrated in Fig. 9, consists of a female die, a spring mounted to the movable ram, and a die punch and filler block. The bottom of the die punch contacts the movable ram, while the top of the filler block, inserted into the die cavity after the powder, contacts the stationary ram.

Since pressing of the blended powders again involves handling finely divided UO_2, hooding is necessary to prevent human intake of airborne activity by ingestion or inhalation. Figure 10 illustrates the dry box containing the pressing dies. The top of the box, not shown, is designed with a hole in the middle complete with rubber gasket which moves along the stationary ram without excessive leakage.

Ten blending jars containing the blended powders, a camel's hair brush, a scoopula, and a bottle of 10 wt % C. P. Stearic acid -90 wt % carbon tetrachloride die lubricant are inserted into the pressing box. By working through the glove ports, stripes of lubricant for each die charge are applied with the 1/4-in. camel's hair brush around the top of the die cavity and the lower sides of the filler block. The die face is occasionally lubricated if it becomes roughened to the extent that the pressed core adheres to it. The powder is poured from a blending jar into the die cavity. The jar is brushed thoroughly with a camel's hair brush to insure complete transfer of all powders. Once the core material has been loaded into the die, it is leveled with a scoopula. The filler block is inserted into the die and the lower ram then raised until the die insert contacts the stationary ram. The blended powders are pressed at 33 tsi pressure (approximately 142 t total pressure) for 15 sec to a thickness of approximately 0.310 in. The filler block is removed and the green compact ejected by elevating the die punch with the hand lever. After ten charges have been pressed, the compacts are loaded into a stainless steel transfer box which is closed and removed from the dry box. A record of the UO_2 lot number is maintained.

5. Sintering of Green Compacts - The sintering operation is carried out in a G. E. 20-kw laboratory molybdenum-wound furnace equipped with a 3-in.

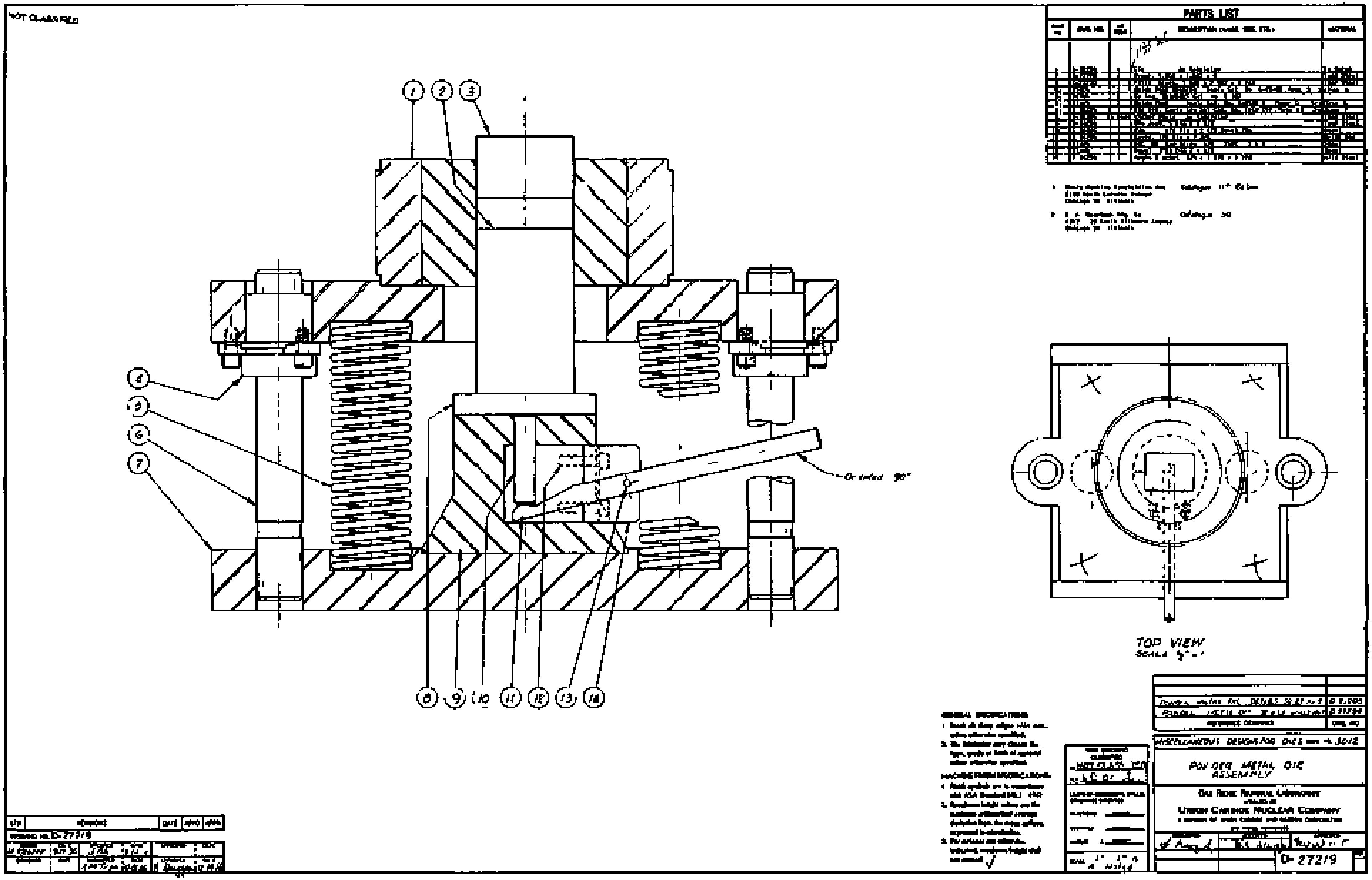

Fig. 9 Powder Metal Die Assembly.

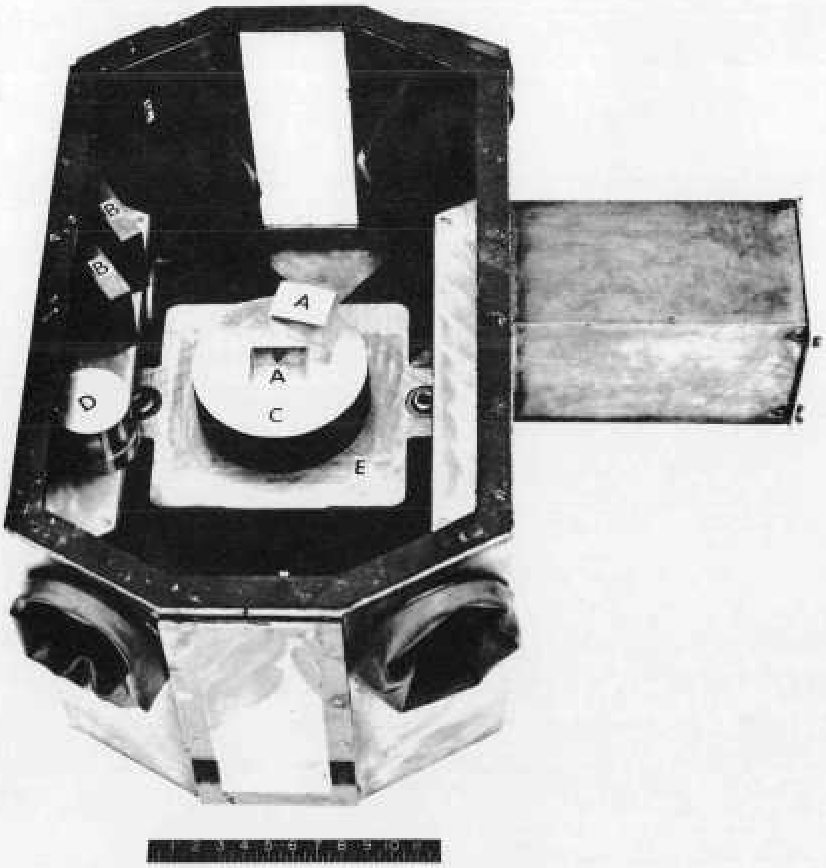

Fig. 10 (Y-13031) Dry Box Arrangement Utilized During Pressing of Powder Blends Containing Enriched UO_2 Powder.

dia Inconel muffle. Thirty-six inches of the muffle extends beyond the furnace and acts as a cooling chamber. The sintering temperature is 2150°F. Uniformity of temperature along the length of compacts is held to ±25°F. Dry hydrogen with a dew point of -60°F, as measured by an Alnor Dewpointer at the gas inlet, is used as atmosphere in the muffle. Hydrogen flow required for this size muffle is approximately 20 cfh under steady-state conditions, although the gas flow is increased when the muffle door is opened during insertion or removal of compacts. The as-sintered compacts do not exhibit any evidence of oxide formation.

The green compacts are placed in a sintering boat constructed of type 316 stainless steel formed into the shape of an "H." The crossbar between the two vertical sides is 2-1/2 in. wide x 14 in. long, and is located approximately 1/2 in. above the bottom of the legs. A piece of type 304, stainless steel, heavy-gauge No. 12-mesh screen is placed upon this cross bar. Five compacts are positioned end to end on this screen, and a second screen is laid over the compacts to allow stacking of a second layer of five cores. The screen permits access of hydrogen gas to all surfaces of the compacts.

The sintering boat containing the ten compacts is inserted in the furnace at 2150°F and the system is purged with hydrogen. The compacts remain at 2150°F for 1-1/4 hr. The boat is moved to the cooling chamber, allowed to cool to 450°F under the hydrogen atmosphere, removed from the muffle, and air-cooled to room temperature. The cores are placed in a covered stainless steel transfer box and moved to the press for coining. A record of UO_2 lot number is maintained.

6. Coining of Sintered Compacts - The shrinkage encountered during sintering makes it convenient for reinsertion of the compact into the same die set for coining. After carefully loading, the sintered compacts are pressed under a pressure of 33 tsi for 15 sec to obtain desirable dimensions and improved densification. The coined compacts are ejected from the die and removed from the dry box. Recoining is sometimes required when the coined compacts are thicker than specified.

7. Inspection - Since it is necessary to predict the U-235 content of the subsequently manufactured fuel element within one gram, it is desirable to weigh the compacts at the completion of fuel core processing. Because of uncertain losses due to reduction of metal oxides by hydrogen during sintering,

it is not practical to consider weight losses of the compact after this operation. The handling losses are, therefore, determined prior to loading the compacts for sintering. A weight deviation of more than 0.25 g from the charged weight for each core is the basis for rejection. If the average deviation of the acceptable core from a batch exceeds this amount the cores are individually weighed for acceptance or rejection. Compacts with obvious chips and flaws, of course, are weighed individually and not included in the batch weighing. After sintering, the compacts are usually examined to determine whether any obvious chipping or spallating has occurred during the handling required for sintering.

The specified thickness after coining is 0.278 ± 0.002 in. and the dimension is measured with a micrometer. Length and width dimensions are established by die design.

8. Core Storage - Each acceptable lot of ten cores is wrapped in paper. These packages are marked with a UO_2 lot number which allows positive identification for accountability. The cores are held in an ordinary desiccator if storage is less than 48 hr. If a storage time of more than 48 hr is required, a vacuum desiccator is used. A maximum of eighty cores is allowed in any one desiccator.

D. Billet Assembly

1. Material Preparation - As illustrated in Fig. 11, each fuel plate billet requires two cover plates and one picture frame in addition to a fuel core. Cover plates are fabricated from 0.078-in. ± 0.005-in. stainless steel sheet which is cold rolled to a thickness of 0.065 in. ± 0.001 in. Cover plates are sheared to 4-7/16 in. x 4-1/2 in. ± 1/16 in. in size. Recommended practice for economical use of material is to reduce 9-in. x 36-in. strips of 0.078-in. sheet to 0.065-in. thickness before final shearing.

Picture frames are fabricated from 5/16-in. stainless steel plate which is cold rolled to 0.280 in. ± 0.002 in. Picture frames are also sheared to 4-7/16 in. x 4-1/2 in. ± 1/16 in. in size. Recommended practice is to cross roll 18-in. squares of the 5/16-in. plate to 0.280-in. thickness before final shearing. A core hole, 1.856 in. x 2.430 in. with 1/8-in. corner radius, is then punched from the center of the picture frame. The blanking die assembly employed for this operation is illustrated in Fig. 12.

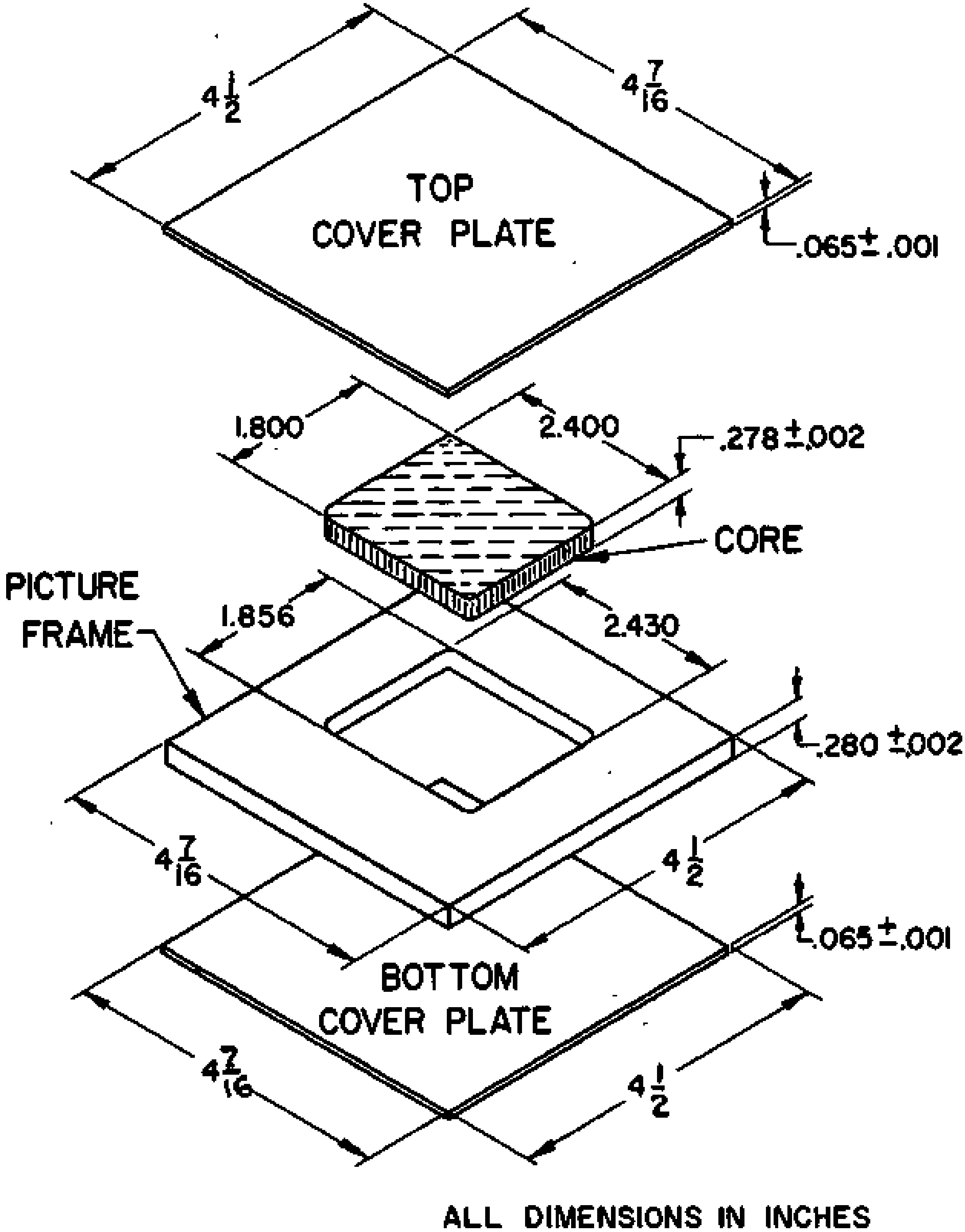

Fig. 11 Exploded View of Composite APPR-1 Fuel Plate Prior to Hot Rolling.

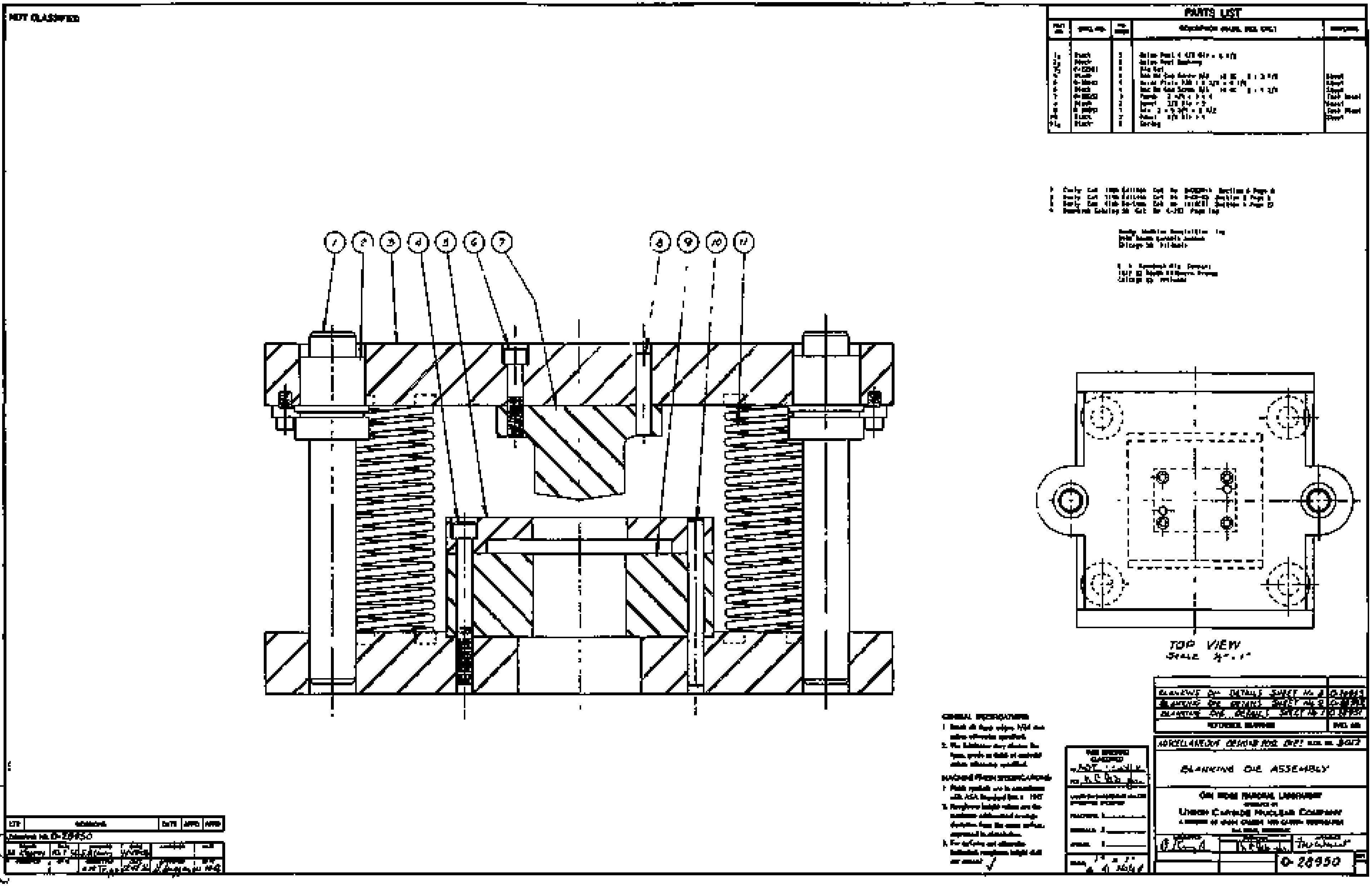

Fig. 12 Blanking Die Assembly.

2. Assembly and Welding of Billets - Immediately prior to billet assembly, both surfaces of the picture frame and the surfaces of the cover plates which contact the picture frame are thoroughly cleaned by scratch brushing with a power-driven stainless steel brush.

The billet is assembled by inserting a fuel core into the hole of the picture frame and placing cover plates on the top and bottom to form a sandwich. One outside edge of one cover plate parallel to the long side of the core is marked with a grease pencil for later identification. The cover plates are immediately resistance spot welded to the picture frame. Four 1/4-in.-dia welds are placed 1/2 in. in from the edge of the billet at the center of each side. A 25-KVA Resistance Welder Corporation Model T-52951 spot-welding machine is used.

The cover plates are also welded to the picture frame plate by the tungsten inert gas method. The object of the welding is to prevent possible shifting of the billet components during initial hot-rolling operations, so that only a seal weld is required. The four corners are left unwelded for a nominal distance of 1/4 in. to permit escape of entrapped air and/or hydrogen during the initial hot passes through the hot-rolling mill. A small projection or "bump" is welded to the center of the edge marked with the grease pencil by adding 18-8 filler metal. This projection identifies the rolling direction and is perpendicular to the 2.4-in. width dimension of the core.

Billets which are not processed immediately are stored in a vacuum desiccator to prevent oxidation. Security, criticality, and accountability regulations dictate careful control during storage. Ordinarily, the billets as well as fabricated plates are stored in a locked safe between processing periods. The shelves of the safe are lined with cadmium. The maximum number of plates that may be stacked in one pile on a shelf is thirty. Minimum separation distance of piles on shelves is four inches.

E. Composite Plate Fabrication

1. Hot Rolling - The assembled and welded billets are hot rolled to a thickness of 0.040 in. ± 0.002 in. on a two-high mill provided with rolls 20-in. dia x 30-in. wide.

The billets are hot rolled in lots of four. However, the lot size is determined by the size of the muffle available for heating the

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billets. A furnace capable of maintaining 2100°F ±25°F over a muffle length of at least 32 in. is recommended. The muffle is purged from the rear with hydrogen gas with a dew point of less than -50°F, as measured at the inlet. A flow rate of 250 cfh is generally used.

The billets are heated to 2100°F for at least 20 min prior to the first pass, and are reheated for at least two minutes between subsequent passes. A second lot of billets is introduced into the furnace for preheating after the sixth mill pass of the preceding plates to allow continuous rolling. After the final pass, the billets are replaced in the muffle for a five-minute anneal, and are then air cooled.

On all billets, the side marked by the weld projection or bump is gripped in tongs so that the opposite edge can be entered into the rolls on the first pass. The billets are rotated about their longitudinal and transverse axes between passes. The hot rolling is performed in approximately ten passes in the following order:

2 passes	at	10% reduction
1 pass	at	20% reduction
4 passes	at	40% reduction
2 passes	at	30% reduction
1 pass	at	20% reduction

Additional passes are made, as required, to roll to 0.040 in. ± 0.002 in. The plate thickness is measured with a micrometer near the end of the fabrication schedule to judge the actual thickness of the hot-rolled plate.

The plates are trimmed in length at both ends by hot shearing during the hot-rolling operation, usually after the sixth and eight passes. The dispersion-type core can be delineated from the wrought stainless steel ends by a difference in heat color. A minimum of four inches of inactive material remains after trimming.

Special care is exercised during rolling to minimize cambering or "rainbowing" of the plates which tends to decrease the amount of stainless steel at the inactive edge and if severe in nature may be cause for rejection. This convex-concave deformation of the plate may possibly be corrected, depending on severity, by inserting the plate through the mill at a slight angle. Gross rainbowing occurring during the hot rolling operation, or during the initial stages of cold rolling, usually cannot be corrected. A level mill and proper feeding are recommended to circumvent this difficulty.

After cooling and prior to fluoroscopic examination, the hot rolled plates are numbered consecutively starting with "1" for the first plate processed. Numbers, one-half inch high, are stamped in the inactive section at either end near the edge of the plate. Each number is entered into the log.

2. Fluoroscopic Examination - The plates are fluoroscoped to delineate the fuel core. A 175-KVP machine is recommended. A template, illustrated in Fig. 13, is used to scribe locating lines for shearing. The template is constructed to locate scribe lines 1/2 in. beyond the sides of the fuel core and 2-3/4 in. beyond the ends, for either long or short plates. The template is centered over the core before the scribe lines are made. The fuel plate number is then restamped with the same stamps previously used and at a location just inside the scribe line at the same end of the plate. A good impression is recommended to assure retention of identification throughout subsequent processing. The as-sheared scribed dimensions of the plate are 3-1/2 in. x 22 in.

After shearing, the hot rolled plates are pickled in a 15% HNO_3-5% HF aqueous solution until all scale is removed. The cleaned plates are thoroughly washed to remove all traces of acid.

3. Cold Rolling - The fuel plates are cold rolled to a final thickness of 0.030 in. ± 0.001 in. Reduction per pass does not exceed 0.001 in.

A Bliss four-high rolling mill with work rolls 5-in. dia x 14 in. wide is used. In order to minimize surface contamination of the fuel plates, these rolls are free of radioactive material. Level rolls and accuracy in elevating and indicating mechanisms are recommended. The roll faces are well lubricated at all times. The entering ends of plates are dipped into SAE-90 oil as required before insertion.

The fuel plates are handled in lots of twenty. At each mill setting, the thickness is measured over the core for the first one or two plates. No guides are used in rolling, but straightness is maintained by continually checking against a straightedge. Deviation from straightness

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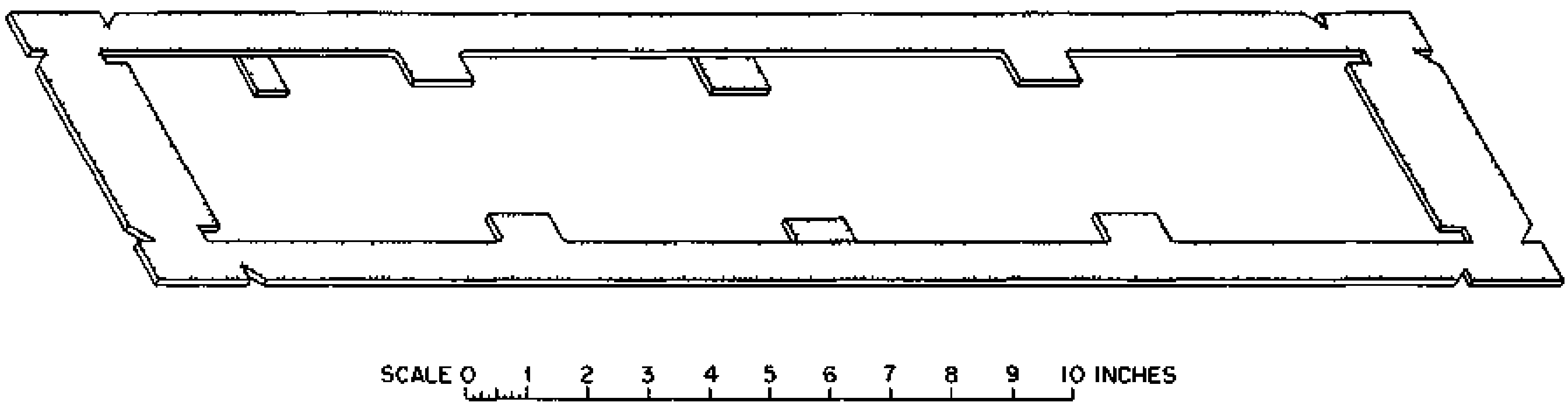

Fig. 13 Rough Shearing Template for APPR Stationary Fuel Plate.

(rainbowing) usually can be corrected if observed at an early stage by insertion of the plate on the next pass at a slight angle.

From thickness in the range of 0.031 in. – 0.032 in., fuel plates are rolled individually to final thickness in one to four passes. Plate thickness at locations above the section containing the fuel core is measured after each pass. After the specified thickness has been attained, the plates are degreased in a vapor degreaser to remove lubricating oil.

Every 25th plate is radiographed to determine the reproducibility of the process with respect to homogeneity of the UO_2.

4. Fluoroscopic Examination and Marking - After cold rolling, the fuel plates are again fluoroscoped for delineation of the core area. A 175-KVP machine is recommended. The template used for both long and short fuel plates is illustrated in Fig. 14. It is slotted at the ends to determine whether or not the core length lies within the minimum and maximum core length dimensions. The side slots are spaced to evaluate whether or not the final fuel core width is within tolerance, and to determine that a sufficient width of stainless steel edging is present along the entire length of the plate. The core is centrally located within the template length limits and with respect to the side slots. Short plate lengths are scribed from the inner end of the template. Long plate lengths are scribed from the outer end of the template. The inner width of the template for scribing allows a sheared plate width approximately 0.080 in. wider than the final-machined width. However, only one side is scribed, since sufficiently accurate shearing of the plate width can be obtained by using a fixed reference stop on the shear bed.

Prior to shearing, the fuel plate number is inscribed with a Burgess Vibro tool in numbers about 3/8 in. high at the plate end inside the scribed line. The number is located far enough on either side of the center line to prevent obstruction by combs located at the plate ends during assembling of the fuel element for brazing.

5. Shearing - The scribed long side is sheared first. Using stops on the shear at a fixed reference, the other long side is sheared to yield a plate width of 2-15/16 in. ± 0.010 in. The ends of the plates are then sheared from the scribe lines to lengths of 23-1/8 in. ± 1/16 in. and 27-1/8 in. ± 1/16 in. for short and long plates, respectively.

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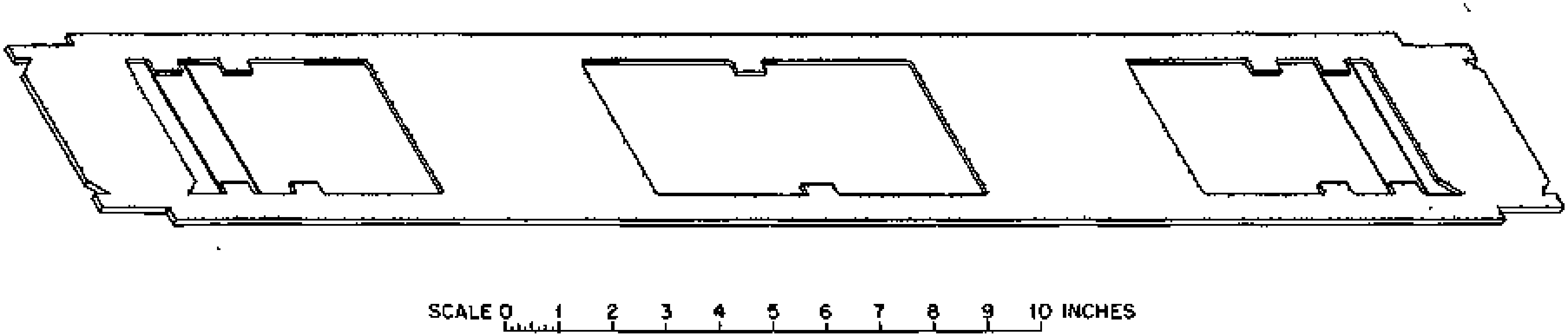

Fig. 14 Final Shearing Template for Either APPR Short or Long Stationary Fuel Plate.

6. Machining - The fuel plates are machined to final dimensions on a horizontal milling machine. The usual lot size for handling is twenty-five. A jig with top and base plates 0.009 in. less in size than the nominal fuel plate width of 2.788 in., and with removable locating brackets, is used to align the plates. The base plate is securely clamped to the milling machine table after proper location. Aluminum cushion plates, 1/8 in. thick, with the same dimensions of the sheared composites are placed on the top and bottom of the lot of plates in the jig. The plates are aligned securely against the locating brackets on one side of the jig. The top plate is positioned and bolted securely at each end through the base plate to the milling machine table. The Allen screws are then tightened to obtain uniform pressure along the length of the fuel plates. The locating brackets are removed.

The side edges of the fuel plates are straddle milled. Two 8-in.-dia staggered-tooth milling cutters are correctly spaced for straddle cutting to finished fuel plate width of 2.778 in. ± 0.002 in.

The ends are then milled on a vertical milling machine using a 4-in.-long side-cutting mill. The lot of plates is clamped to the table over a block. An effort is made to remove equal amounts of stainless steel from each end of the fuel plates. Final lengths are 23 in. ± 1/64 in. and 27 ± 1/64 in. for short and long plates, respectively.

After degreasing in a vapor degreaser, the machined edges of the fuel plates are lightly deburred by hand-filing. Special care is taken to prevent rounding of the edges.

7. Inspection - The fuel plate dimensions specified in Fig. 15 are given a final inspection by fluoroscopy on a 175-KVP machine. The final inspection templates, shown in Figs. 16 and 17, are constructed on the go, no-go principle. Minimum core width of 2.500 in. and maximum width of 2.578 in., as well as inactive edge minimum and maximum widths, are inspected with this template. Width inspection slots are spaced 2.500 in. apart and are 0.039 in. wide. The width between the outer edge of the slot and the edge of the template is 0.100 in. Length inspection slots are spaced to determine whether or not the core length lies within the 21-in. minimum and 22-1/2-in. maximum specified.

Fuel plates that fail this inspection are radiographed. Core length, core width, and width of inactive stainless steel edging are

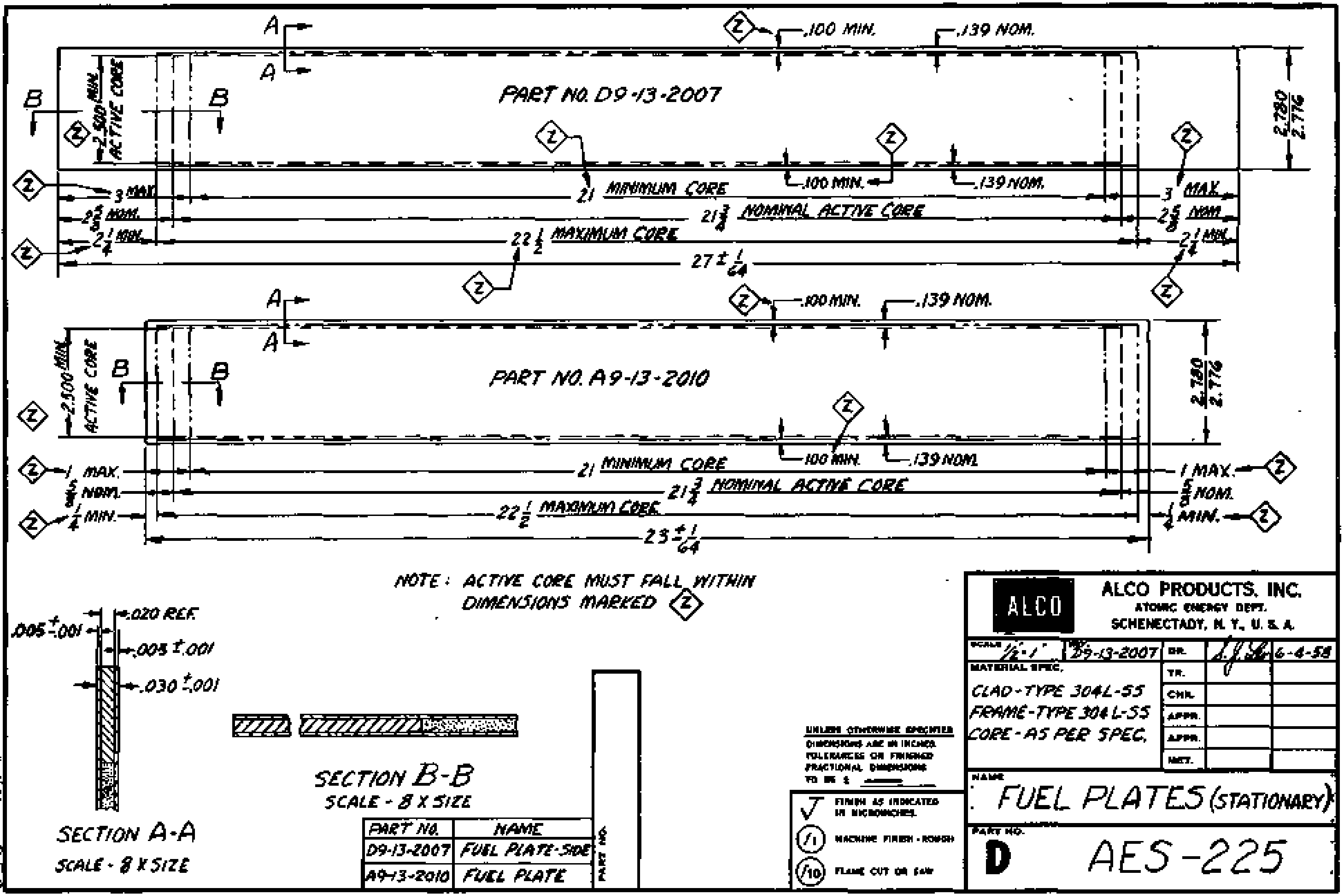

Fig. 15 Stationary Fuel Plates.

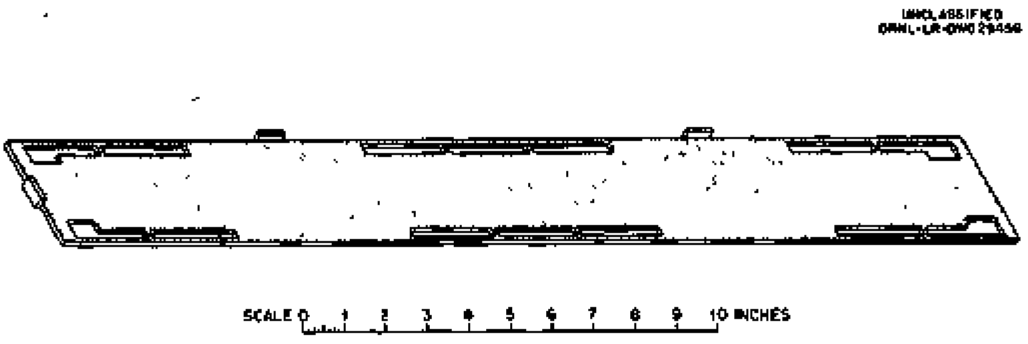

Fig. 16 Final Inspection Template for APPR Short Stationary Fuel Plate.

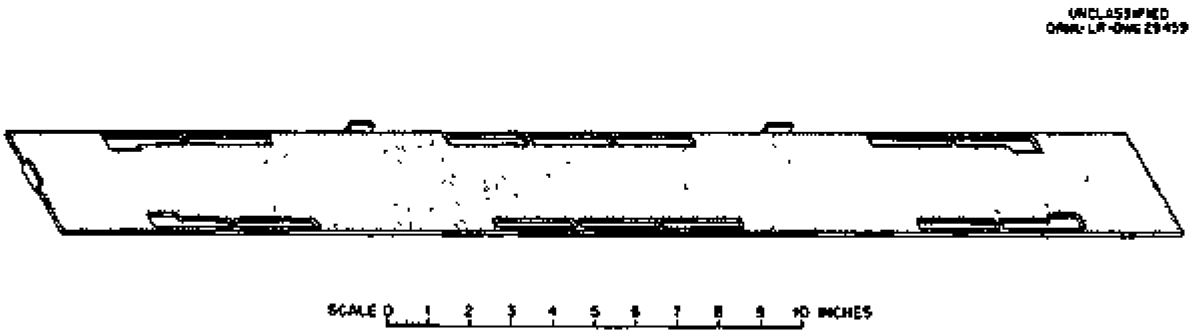

Fig. 17 Final Inspection Template for APPR Stationary Long Fuel Plate.

measured directly from the X-ray film. Plates which do not meet dimensional requirements are rejected. The surfaces of the fuel plates also are inspected for defects. Oxide indentations, pits, and scratches deeper than 0.001 in. are cause for rejection. Dents, blisters, and discrete color changes on the surface are also cause for rejection.

F. Flatten Annealing of Machined Fuel Plates

To facilitate assembling of the fuel plates into an array and to meet plate spacing dimensions in the brazed fuel unit, it is necessary that the composite plates be flat and fully annealed. The flattening and annealing is accomplished in one operation. Accepted fuel plates are degreased in a vapor degreaser prior to annealing. Lot size for flatten annealing is twenty-five fuel plates.

Each plate is covered on one side with a thin coat of a mixture containing one part by volume of Fisher 5F Precisionite levigated alumina and ten parts of water. A three-inch camel's hair brush is used to apply an even coating. The coated fuel plates are allowed to dry for at least 15 min.

As illustrated in Fig. 18, a jig composed of two platens for clamping the fuel plates together is used for this operation. Twenty-five fuel plates are stacked together with the coated side adjacent to the uncoated side. The stack is placed between the platens, and the clamping bolts are firmly tightened. The loaded assembly is dried in an oven at 330°F for a minimum of 16 hr.

The annealing temperature is 2100°F ± 25°F and the annealing accomplished within an Inconel muffle inserted in a 56-kw Globar furnace. The muffle has a cross sectional dimension of 7 in. x 9 in. and is 6 ft in length. Bright annealing of the plates is obtained under a purge of dry hydrogen with a dew point of -80°F, as measured by an Alnor Dew-pointer at the furnace inlet.

Furnace temperature at insertion of the loaded platen assembly ordinarily does not exceed 570°F. The muffle is purged with helium prior to insertion of the plates and during the period of heating between 570°F and 1200°F. The temperature is raised to 1200°F at a rate not exceeding 540°F per hour. At 1200°F the helium atmosphere is replaced by hydrogen. A flow rate sufficient to bright anneal stainless steel is recommended; 240 cfh is used generally. The temperature is raised to 2100°F at a rate

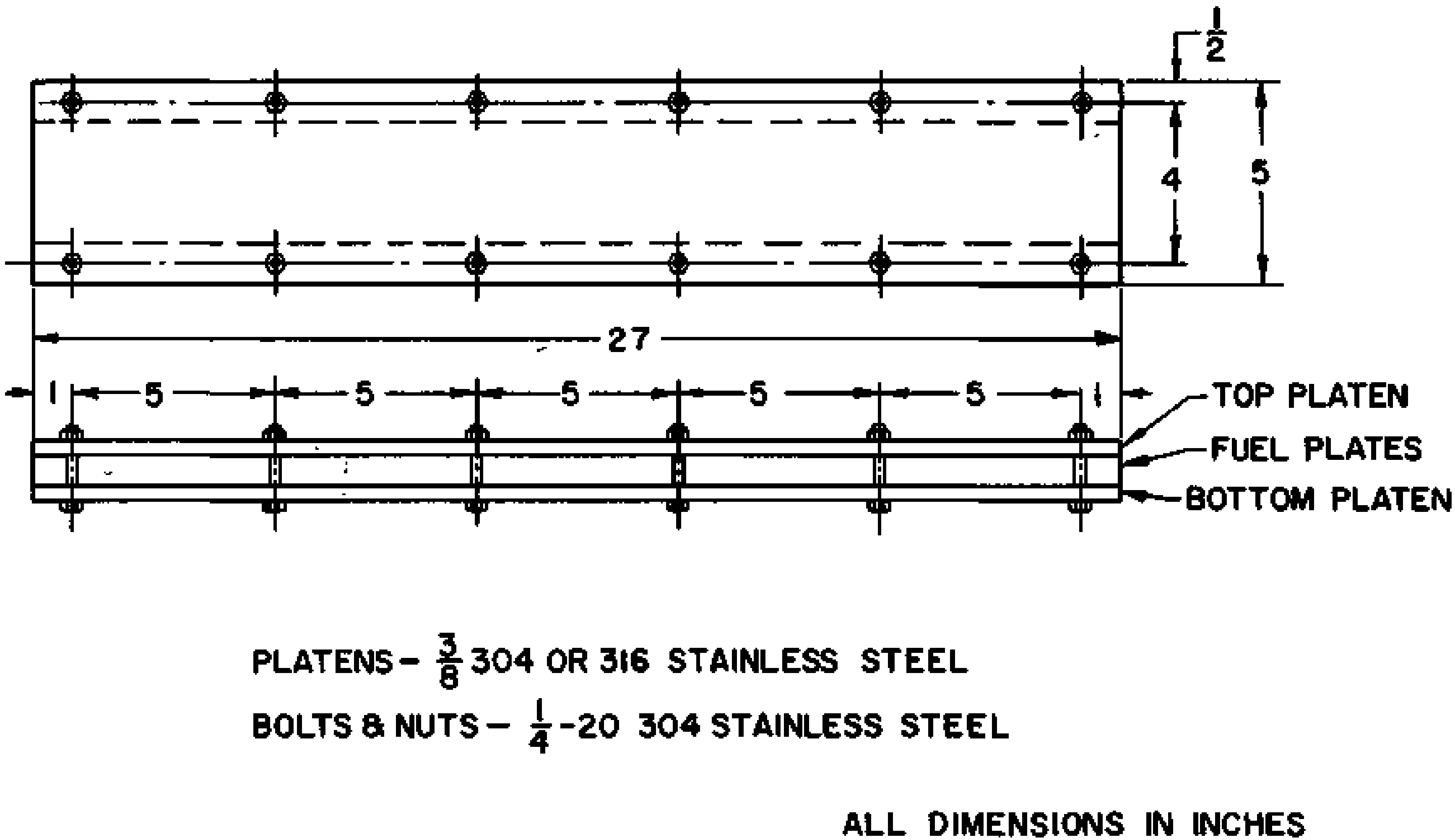

Fig. 18 Assembly for Flatten Anneal.

of approximately 540°F per hour. The plates are held at 2100°F for two hours, and then furnace cooled to 570°F. At this temperature, the hydrogen atmosphere is replaced with a helium purge. The assembly is then removed from the muffle and air cooled. After disassembly, the fuel plates are scrubbed under flowing water to remove the coating of alumina. Care is exerted in this scrubbing treatment to prevent distortion of the fuel plates. The fuel plates are then either air or oven dried. The surfaces of the fuel plates again are inspected for defects and accepted plates are stored in a safe. Oxide indentations, pits, and scratches deeper than 0.001 in. are cause for rejection. Dents, blisters, and discrete color changes on the surface are also cause for rejection.

G. Manufacture of Side Plates and Combs

1. Side Plates -

a. Machining

The side plates are machined from 0.050 in. ± 0.003 in. stainless steel sheet stock, sheared to 27-1/4 in. x 3-1/4 in. ± 1/16 in. in size. Each plate is deburred with a file after shearing. A stack of twenty plates is sandwiched between two pieces of 1/8-in.-thick aluminum sheet of approximate side plate dimensions to prevent distortion of the side plates during the milling operation. The assembly is table-clamped lengthwise and straddle milled on a horizontal milling machine. Two 8-in.-dia staggered-tooth steel cutters rotating at approximately 20 rpm with a 1/2-in./min feed are used to mill the stack of plates to final width in one pass. The assembly is then transferred to a vertical milling machine, and machined to the proper length with a side cutting mill rotating at 150 rpm with a 1-in./min feed. Dimensional requirements are specified on Alco Drawing D9-13-2014.

Each side plate is completely deburred with a file to insure a good grip by the vacuum chuck employed during the grooving operation. The chuck is 36 in. x 12 in. with vacuum holes on 1/2-in. centers. Holes not covered by the side plate are covered with two layers of heavy masking tape. The vacuum for the chuck is supplied by a large industrial vacuum cleaner.

During the grooving operation the eighteen grooves per plate are cut in one pass on a horizontal milling machine using 3-in.-dia x 0.034-in.-thick carbide-tipped slitting-saw blades. Special care is exercised in establishing the location of the saw blades on the machine arbor to insure that the dimensions between grooves and edges of the side plates are correct. The cutters rotate at 60 rpm with a feed of about 1-5/8-in./min. A heavy sulphur-base cutting oil is used for lubrication.

b. Inspection

Subsequent to machining and grooving, the plates are degreased and each plate dimensionally inspected. The plate groove depths are determined either by gauge wire with a micrometer or by a thin roller attached to a dial indicator. The groove separations are measured with a micrometer from plates inserted in the grooves or with a disc type micrometer. All dimensions must fall within the tolerances specified on Alco Drawing D9-13-2014.

c. Flatten Annealing

Flatten annealing of the side plates is required to relieve the stresses which occur during the grooving operation. The side plates are annealed in a manner identical to that used in annealing the fuel plates described in Section D with the following exceptions:

1. The individual side plates are separated by 0.030-in.-thick, type 304L stainless steel shim stock.
2. The alumina mixture is applied to both sides of the shim stock. The side plates are not coated because of the difficulty in removing the alumina from the grooves.
3. A maximum of fifteen side plates are stacked with the alumina-coated shims between each plate.

2. Combs -

a. Machining

The combs, shown on Alco Drawing D9-13-2014, are made from 0.050-in. ± 0.003-in.-thick stainless steel sheet sheared to 3 in. x 1 in. ± 1/16 in. Stock is usually selected from trimmings remaining from side plate shearing. The length is milled to final size. The width is milled 1/4 in. oversize to provide sufficient stock for holding during the slotting operation. Slotting of the combs is performed on a horizontal milling machine with a high-speed steel screw-slotting cutter rotating at 60 rpm with a 1/2-in./min feed. A group of fifteen to twenty combs is held by the excess material on the width in a precision vise mounted on the table of a milling machine. Each slot is machined individually. After complete slotting, the pieces are mounted in a precision vise and are machined on a shaper to remove the excess width stock.

b. Inspection

Each comb is dimensionally inspected. The comb groove width and location are checked in the same manner as the side plates. The length, width, and thickness of the combs are checked with conventional micrometers. Combs not meeting the dimensional tolerances specified on Alco Drawing D9-13-2014 are rejected. Following inspection, the combs are vapor degreased and stored for future use.

H. Assembly of Fuel Unit

1. Brazing Jig - A combination assembly and brazing jig is utilized for assembling the fuel plates, side plates, and combs into a fuel assembly. Any type of 300-series stainless steel with expansion characteristics approximating that of 304L stainless is satisfactory as the jig material.

As shown in Fig. 19, the base plate of the jig is made from one-inch stock to which longitudinal bottom skids are attached. Five "U" shaped supports are located in a shallow groove machined in the baseplate and are attached to the baseplate by means of dowel pins and screws. To allow for flexibility in assembly, the inside dimension of the "U" supports is approximately 0.100 in. larger than the actual finished width of the brazed assembly. A shim plate between each side of the "U" support and the respective side plate compensates for the gap. The thickness of the shims used in assembling an individual fuel assembly is determined prior to assembling. A sample calculation is shown on the following page.

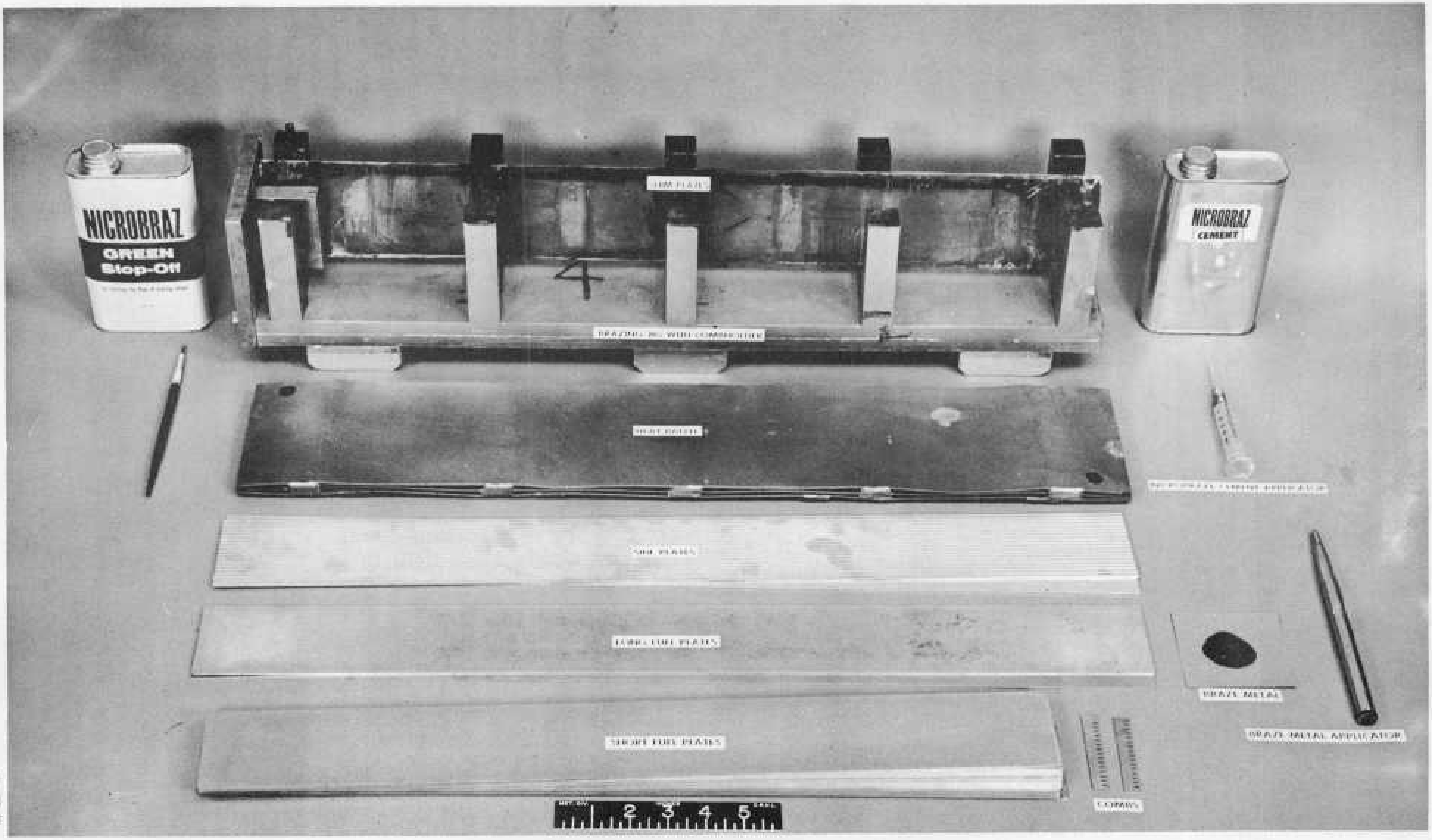

Fig. 19 (Y-25949) Components for Brazing APPR Fuel Element Assembly.

Inside dimension of brazing jig "U" supports:	2.940 in.
Fuel plate width:	2.778 in.
Side plate thickness (measured from base of grooves):	0.025 in.
Braze metal clearance (measured from bottom of side plate grooves to edge of inserted fuel plate):	0.005 in.

Total Shim Thickness $= a - (b+2c+2d)$

$= 2.940 \text{ in.} - [2.778 \text{ in.} + 2(0.025 \text{ in.}) + 2(0.005 \text{ in.})]$

$= 0.102 \text{ in.}$

With a total calculated shim thickness of 0.102 in., 0.051-in. shims or a combination, such as 0.050-in. and 0.052-in. shims, are used.

A removable comb holder is located by two dowel pins at one end of the jig and attached to the base plate with machine screws. This holder is used only during assembly and is removed prior to insertion of the jig and the fuel plate assembly into the brazing furnace.

2. Procedure - Immediately prior to assembly, the surfaces of the fuel plates are inspected as previously described in Section C-7.

a. The size of the shims to be used is determined.

b. The two selected shim plates are then positioned, one against each side of the "U" uprights.

c. Two side plates, with grooved sides facing each other, are placed adjacent to the shim plates and positioned snug against the mounting plate of the comb holder. A scrap piece of stainless steel sheet stock is inserted to hold the side plates flat against the jig supports.

d. A long fuel plate is inserted from the open end of the jig into the bottom groove of the side plates and positioned snugly against the mounting plate of the comb holder.

e. The jig is tilted about the horizontal axis to facilitate placing of the braze metal, cement, and stop-off. This is accomplished by using a 1.5-in.-thick piece of wood to elevate one side of the assembly.

f. As shown in Fig. 20, the dry Coast Metals N. P. braze metal is applied by gravity from a stainless steel pointed tube resembling the barrel of a mechanical pencil. It is important that

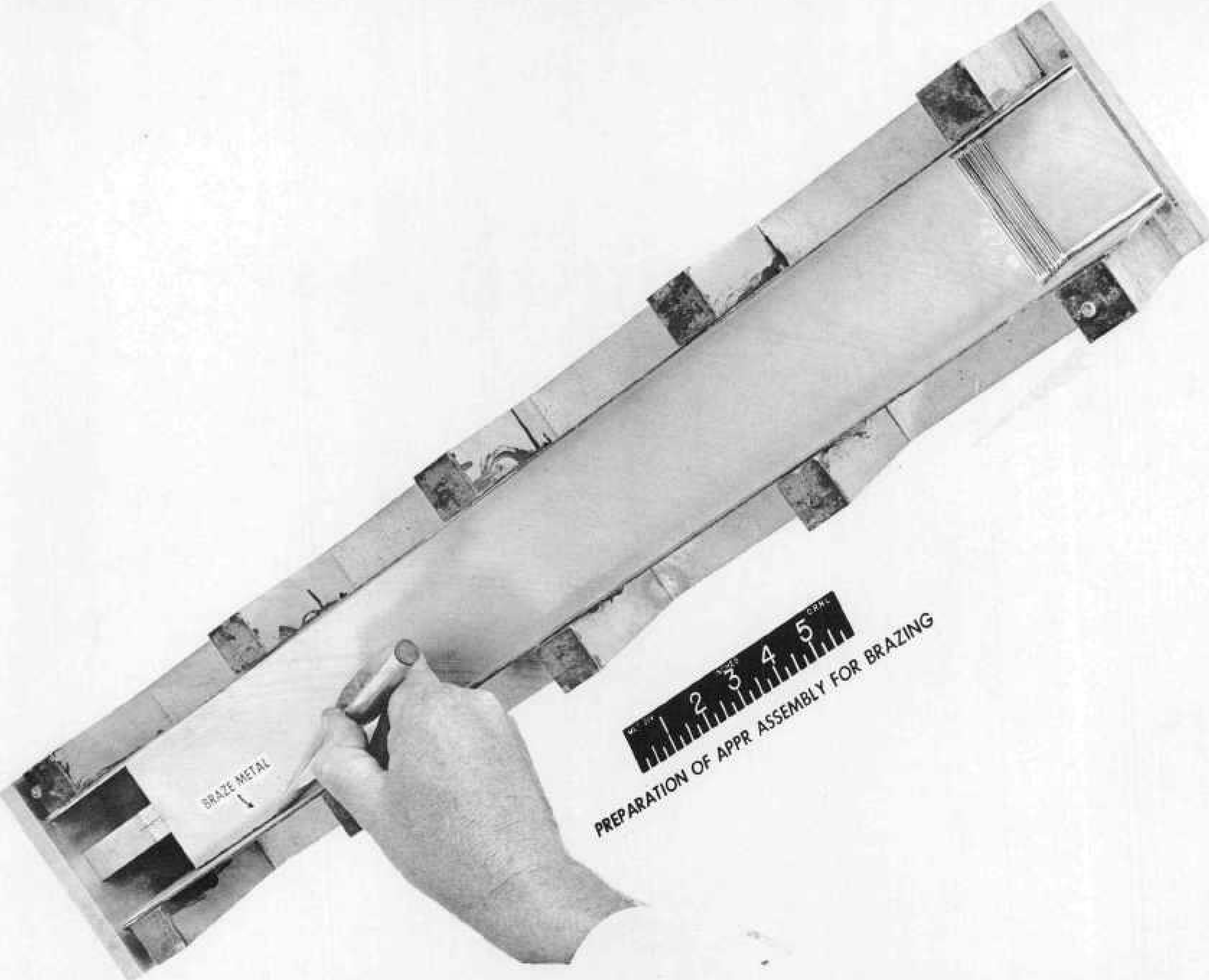

Fig. 20 (Y-25951) Application of Braze Metal.

the braze metal be confined to the inactive edge of the plate and not preplaced on the cladding surface above the fuel core. Since the minimum specification of the width of the inactive stainless steel edge of the fuel plate is 0.100 in. and 0.025 in. is the maximum distance the plate can be inserted in the side plate groove, a mere 0.075-in. wide strip of inactive stainless steel remains for preplacement of braze powder. It is recommended that the width occupied by the braze powder be less than 0.060 in.

g. As shown in Fig. 21, the dry braze metal powder is cemented into place with Colmonoy Nicrobraz Cement. A 19-gauge hypodermic needle attached to a 5-cc syringe permits the cement to drip by gravity onto the fuel plate adjacent to the braze metal fillet. The cement is allowed to dry for 30 sec.

h. As illustrated in Fig. 22, a one-fourth-inch wide strip of Colmony Green Stop-off is applied with a camel's hair brush directly adjacent to the braze metal on the active portion of the plate. The stop-off is used to prevent the braze metal from flowing laterally onto the stainless steel cladding of the active core section during the subsequent brazing operation.

i. The wood tilting block is then moved to the opposite side of the jig, and operations "f" through "h" are repeated for the opposite fuel plate-side plate joint.

j. A comb is placed in the comb holder, and the braze metal, cement, and stop-off are applied in succession to the long comb-long plate joint.

k. A short plate is inserted in the second row of side plate grooves and firmly placed in the comb groove.

l. Steps "f" through "i" are repeated with the addition of filling the comb-to-plate joint with braze metal, cement, and stop-off.

m. The process is repeated, inserting plates from bottom to top, until all joints of the sixteen short plates have been properly prepared with braze powder, cement, and stop-off.

n. The second comb is attached to the unit prior to inserting

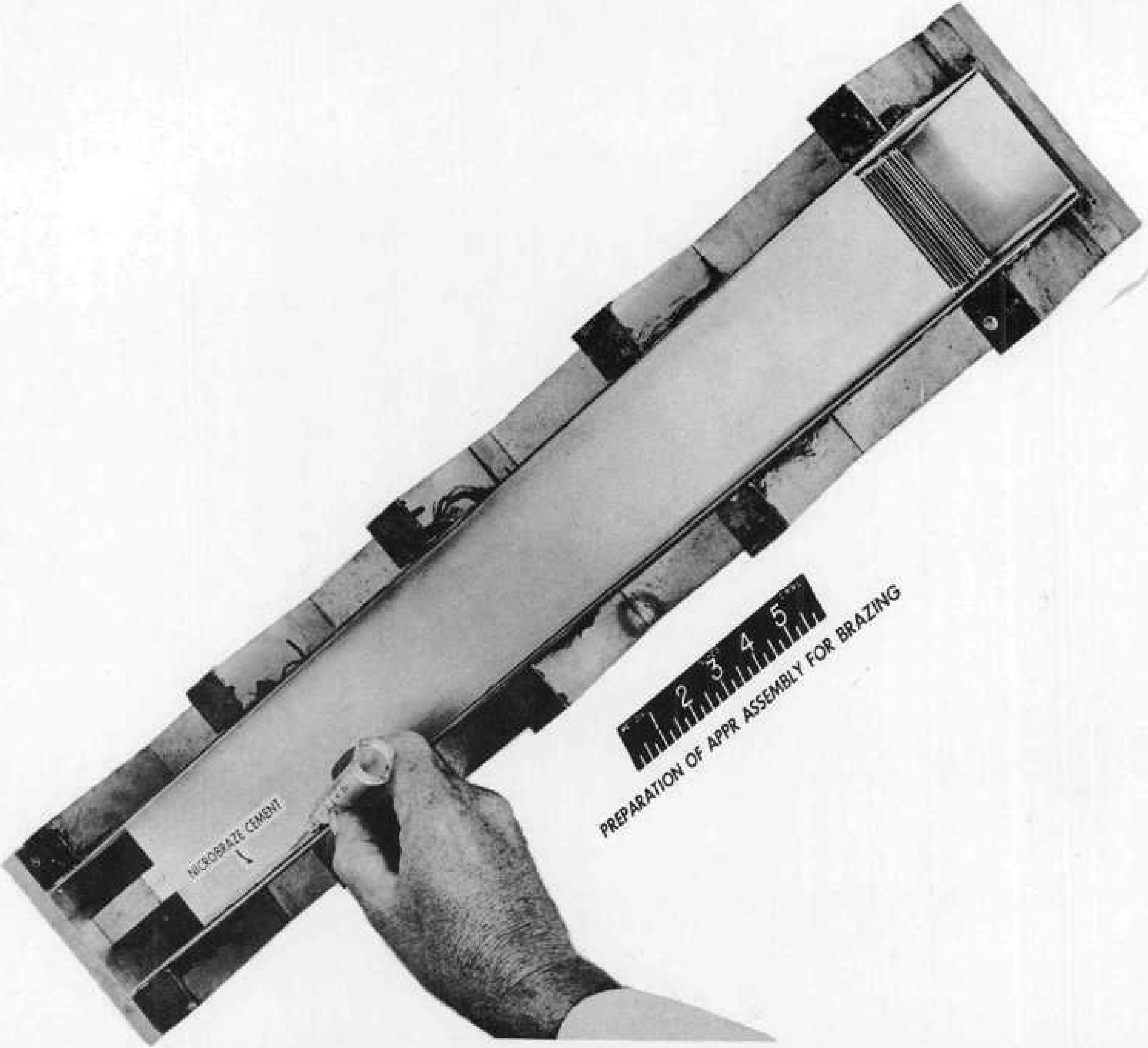

Fig. 21 (Y-25952) Application of Nicrobraze Cement.

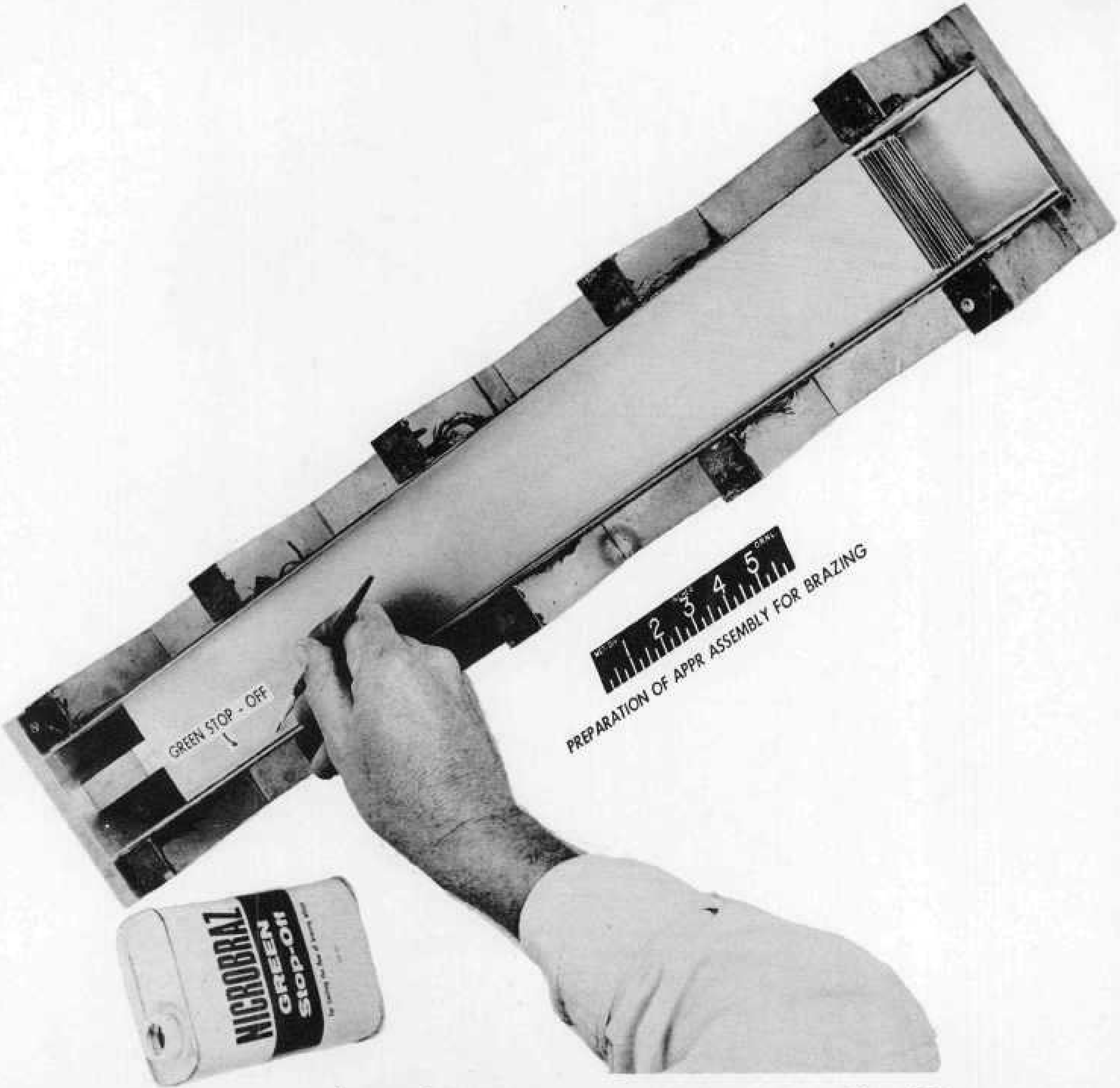

Fig. 22 (Y-25953) Application of Nicrobraze Green Stop-Off.

the top long fuel plate into the side plate grooves. All comb-fuel-plate joints are filled with braze metal, cement, and stop-off.

o. The joints of the top long fuel plate are prepared in the same manner as the bottom long plate.

p. The comb holder is removed from the jig and the complete jig and assembly rotated 90 deg. The brazing materials are then applied to the long fuel plate-comb joint.

q. As shown in Fig. 23, a one-half-inch wide strip of Colmonoy stop-off is made across the side plate inside the assembly one-half inch beyond the ends of the short fuel plates. This strip prevents the braze metal from flowing to the ends of the side plate during brazing, which may cause difficulty in welding end adapters to the brazed fuel unit.

r. The disposition of the fuel plates is identified with the fuel element number in the master log.

I. Brazing of Fuel Assemblies

1. Procedure - Brazing of fuel elements is accomplished in the identical furnace equipment utilized for annealing fuel plates. The furnace is equipped with a leak tight muffle for maintaining a dry hydrogen atmosphere and is capable of maintaining a maximum gradient of 5°F along the entire fuel assembly length at the brazing temperature.

Two calibrated chromel-alumel thermocouples are attached (one to the front and the other to the rear) to the assembly. Each thermocouple is checked at room temperature prior to acceptance. The rear thermocouple leads extend along the baseplate between the jig skids, and the junction is inserted a distance of two inches from the rear of the fuel element between the middle fuel plates. The front thermocouple is similarly located between the middle fuel plates by inserting the leads directly into the front of the element.

A heat baffle is placed on top of the jig to minimize temperature gradients during the heating and cooling cycle. This baffle consists of three 0.050-in.-thick 18-8 stainless steel plates, separated 1/8 in. by spacers and welded to form an integral unit. The jig containing the assembled fuel unit, complete with thermocouples, is placed in the furnace

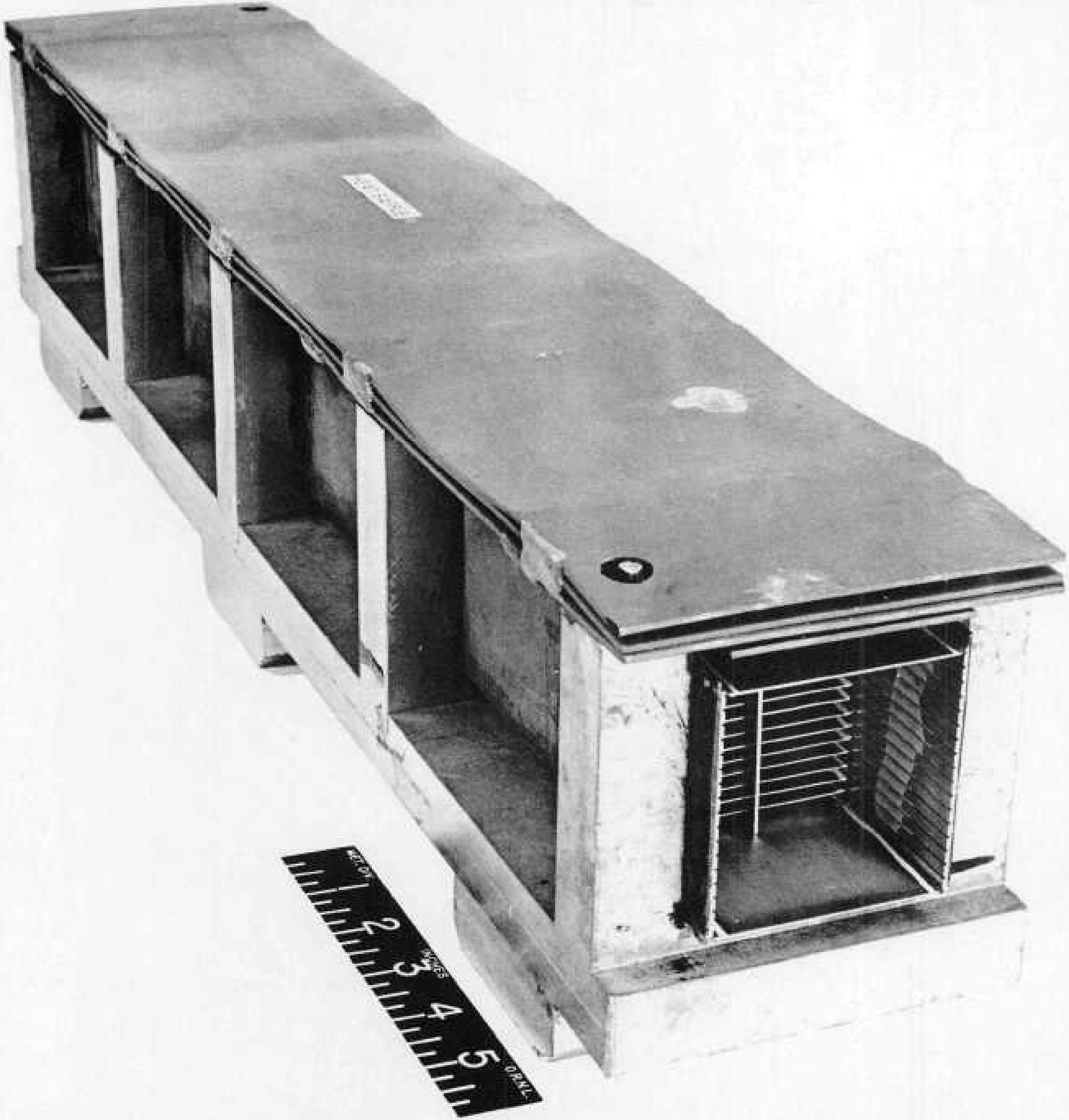

Fig. 23 (Y-25957) APPR Fuel Assembly Ready for Brazing.

at a maximum temperature of 570°F. A dry helium atmosphere, with a minimum dew point of -40°F, as measured by an Alnor Dewpointer at the inlet end, is introduced as the atmosphere at low temperatures. A pair of stainless steel reflector shields are placed in front of the jig to minimize thermal gradients along the fuel element. The thermocouple leads on the fuel element are threaded through the furnace door entry port.

The furnace temperature is raised to 1200°F at a rate not to exceed 370°F per hour. The furnace is held at this temperature until the temperature gradient, as measured by the thermocouples, is less than 45°F. At this time, dry hydrogen with a dew point of at least -80°F is introduced and the helium purge discontinued. The temperature is raised to 1830°F, and is held until the temperature gradient is less than 18°F and outlet hydrogen dew point is at least -50°F. The furnace temperature is raised to 2010°F and the fuel element is held at this temperature until the temperature gradient is less than 5°F.

Above 2010°F, the furnace temperature is slowly raised by careful manual control. Temperature readings are taken on both the thermocouples every minute. The temperature gradient is maintained as low as possible, with a maximum of 5°F. When the thermocouple temperatures reach 2071°F, the furnace is shut off. The total time for the fuel assembly above 2066°F, as measured by the thermocouples, does not exceed eight minutes. The brazed fuel assembly is furnace cooled to 570°F, at which temperature the furnace is purged with helium. After thorough purging, the furnace is opened and the assembly air-cooled to room temperature. The total time for one complete brazing cycle is approximately 24 hr.

After the brazing operation, each completed assembly is identified with numbers approximately one-half inch high. A Burgess Electric Vibro-Tool with a tantalum-carbide tipped point is used for marking. Completed fuel assemblies are consecutively marked starting with "1" for the first assembly. Appropriate records are maintained in the master log.

2. Dimensional Inspection - The brazed fuel assemblies are dimensionally inspected for plate spacing, element width and sag or distortion of top and bottom plates. The data for each assembly are recorded on an appropriate inspection form.

Plate spacings are measured at the centers of fuel plates at distances of 2-1/2 in., 10 in., 17 in., and 24-1/2 in. from the numbered end. Sixty-eight readings per fuel element are obtained. Maximum allowable deviation is ±10% of the nominal spacing, or 0.013 in. Fuel elements with deviations greater than 0.013 in. are rejected.

Air gauging to measure plate spacings is not acceptable. As shown in Fig. 24, a special measuring device incorporating a calibrated elliptical probe has been successfully used. A steel illipsoid, having 0.100-in. minor and 0.150-in. major axes, is mounted on the end of a 0.100-in.-dia tube approximately 27 in. long. A one-inch-thick plastic block, 3 in. x 6 in., with a hole in the center allowing tube rotation, is mounted near the other end of the tube. A needle indicator is rigidly mounted on the tube near the plastic block parallel with the ellipsoid major asix. The needle is calibrated by rotating the ellipsoid between gage blocks and the width of space between gage blocks marked on a piece of polar graph paper. The calibrations are fastened on the face of the plastic block.

The width of the assembly is measured with a 3-in. micrometer at six locations along the top and bottom of the side plates for a total of twelve measurements per assembly. Measurements are taken at distances of one, six, eleven, sixteen, twenty-one, and twenty-six inches from the numbered end of the element. Fuel assemblies with width dimensions outside the limits of 2.844 in. -0.022 in. +0.000 in. are rejected, unless specifically approved by the Contracting Agency.

The dimensions from the outside center of the top and bottom fuel plates to the edges of the side plates is measured with a depth micrometer at locations of 2-1/2 in., 9 in., 15-1/2 in.,and 22 in. from the numbered end of the fuel assembly for a total of eight measurements. Fuel assemblies with measurements outside the limits of 0.033 in. ± 0.013 in. shall be rejected.

3. Cleaning - The fuel assemblies are cleaned under hot water to remove the stop-off residue by scrubbing with a 1/8-in.-dia stainless steel wire brush. Care must be exercised to prevent damage to the fuel plates.

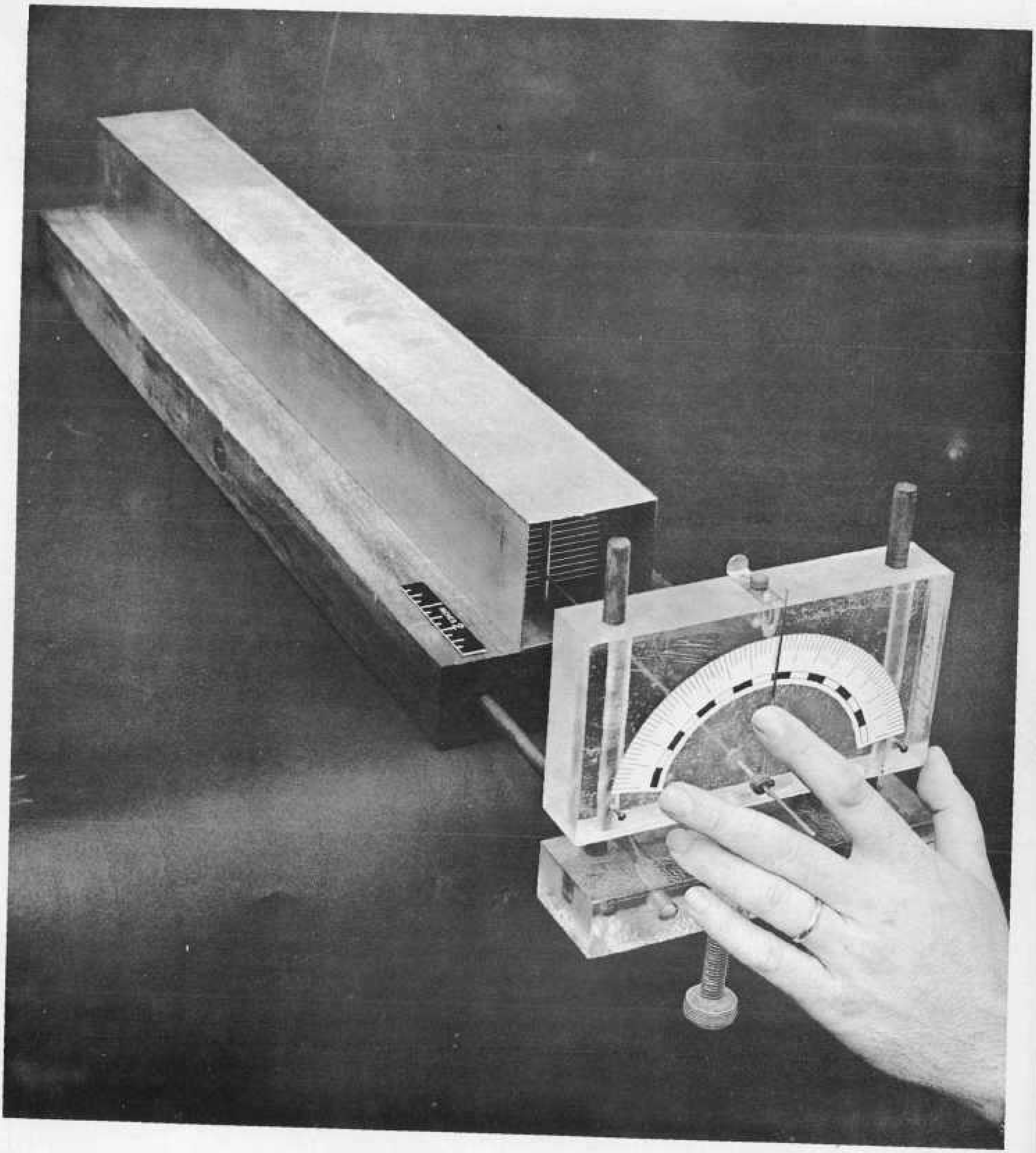

Fig. 24 (Y-26540) Plate Spacing Guage.

4. Visual Inspection - The fuel plates in the assemblies are visually inspected for defects, such as blistering, dents, and scratches over 0.001 in. in depth. The presence of any of these defects is cause for rejection. The brazed joints and the fuel plates are visually inspected for splatter, lateral spread of braze metal, and pitting. Any splatter, lateral spread over the core or pitting is cause for rejection.

J. Attachment of End Adapters and Final Machining

1. Preliminary Machining of Brazed Assemblies - Two parallel vises are mounted on a vertical milling machine table with the faces of the vises parallel to the lengthwise table feed. The vises are spaced apart so that approximately one-half inch of the fuel assembly will extend from the outer edge of each vise. The vise jaws are carefully tightened against the side plates. Both ends of the assembly are squared and a length of 27 in. ±1/64 in. is obtained by cross traverse of the table using a 4-in.-long side-cutting mill. The edges are carefully deburred with a file.

2. Preliminary Machining of End Boxes - End adapters, described in Alco Drawings C9-13-2022, C9-13-2023, are attached to each end of the fuel assembly to locate the fuel elements in the grid plates of the reactor core, and to direct the coolant flow along the fuel plates. Over-all economic considerations may be a factor in the selection of the type of casting. Sand castings may require machining of the bore for locating purposes, and hand polishing of the entire unmachined portion of the bore to obtain the required 125 RMS surface finish.

In machining the end boxes, a split or expanding mandrel is mounted vertically with the "solid" end of the mandrel attached to a support plate bolted to the milling machine table. The end box, bored end down, is placed on the mandrel and the mandrel is expanded. The end box is located so that wider dimension of the rectangular surfaces is parallel to the travel of the table. These surfaces are straddle milled to 2.863 in. ±0.002 in. For machining the other dimension of the rectangular surfaces, the end box is located by reference perpendicular to the previously machined surfaces. These surfaces are straddle milled to 2.844 in. $^{+0.000\text{ in.}}_{-0.022\text{ in.}}$

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This fixture is also used to locate and hold the end boxes during machining of the male end connections which are inserted into the brazed fuel assembly. An interference fit of 0.002 in. in both directions requires individual selection and machining of end boxes to each fuel assembly. These surfaces are side milled to provide the necessary fit and the end boxes are inserted into the appropriate brazed assembly for storage. Hand polishing of the unmachined bore may be required to obtain a finish of 125 RMS.

3. Assembly - The fit of the end boxes into the brazed assembly is adjusted so that a gap of 1/32 in. is left between the ends of the side plates and the end box shoulders. Three-inch "C" clamps are placed across the middle of the side plates to hold the end boxes in place. The clamped assembly is placed on two matched parallel bars on a surface plate. The bottom inner surface of the end box bore is zeroed on a dial indicator mounted on a surface gauge. The indicator is removed and the assembly is turned 180 deg. The new bottom of the bore is indicated. Misalignment is adjusted by tapping with a plastic hammer until dial-indicator readings vary by no more than ±0.001 in. The fuel assembly is rotated 90 deg and the above procedure repeated. The clamps are checked for tightness. The other end box is similarly adjusted. The center lines of the end boxes are thus aligned with the center line of the fuel assembly.

4. Welding of End Boxes - A rotatable jig is used to hold and position the assembly during fuel assembly to end box welding. The jig consists of a rotatable base plate to which the fuel assembly is strapped two inches from each end of the brazed assembly. A ring is also attached at each end of the baseplate through which four locating thumb screws are extended. The assembly is clamped to the baseplate and the four thumb screws are carefully tightened to contact the end boxes. The "C" clamps remain in place during the welding operation.

The fuel elements are butt welded to the end boxes using the tungsten inert-gas process with argon gas and 308L bare filler wire. Only the side plates are welded to the end boxes, using the following procedures: A tack is made at the center of one side-plate joint; another tack is made at the center of the other side-plate joint; the first joint is welded over the full length and the second joint is then welded; the welds are made flush with the side plates; and the second end box is then welded in the identical manner.

5. Final Machining of Fuel Elements - The fuel element with the end boxes attached is placed in an engine lathe for final machining, with the inlet end box at the headstock. A standard expanding mandrel is inserted into the center bore of each end box and expanded. The mandrels are supported in the lathe between two four-jaw chucks. The element is properly located in the chuck so that the jaws move perpendicular to the sides of the fuel element. This permits shifting of the element in any of four directions for proper alignment.

The element is centered with its center-line axis "Y", indicated by points "D" and "E", shown on Alco Drawing R9-13-1003 (Fig. 25), coinciding with the lathe center line. This is done by first indicating the outside surface of the top fuel plate with a dial indicator mounted on a surface gauge placed on the lathe bed. The element is then rotated 180 deg, and the outside surface of the bottom fuel plate is indicated. If zero readings are not obtained for both top and bottom fuel plates, the element is shifted by adjusting the jaws of the chuck until both surfaces are zeroed in. The element is rotated 90 deg, and the same indicating procedure is followed until zero readings are obtained on the outside surfaces of both side plates. Center-line axis "Y" is rechecked in the first plane for alignment, and corrected if necessary.

The round portion of the inlet end box in the headstock is then rough machined to 0.005 in. greater than the finished dimensions. The element is again rechecked for alignment in both planes of the center line "Y". The round portion is machined to the finished dimensions of 2.495 in. + 0.000 in. - 0.002 in. Subsequent to final machining of the inlet end box, the fuel element is reversed in the lathe so that the outlet end box is positioned at the headstock. The above procedure is then repeated for the outlet end box.

The fuel assembly is removed from the lathe, and the mandrels are slipped from each end box. The fuel element is then placed in two parallel precision vises mounted on a vertical milling machine table. The

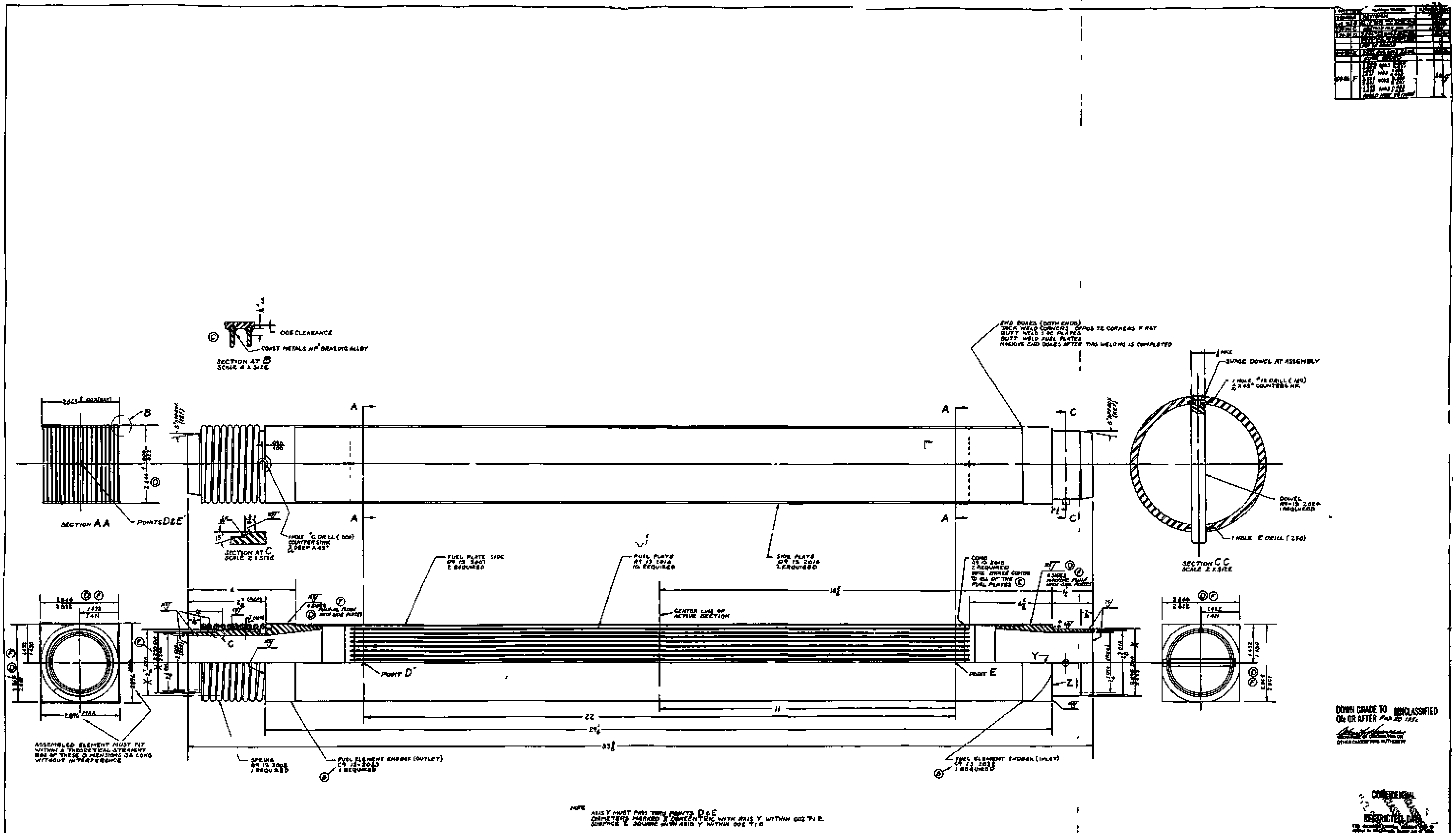

Fig. 25 Stationary Fuel Element.

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vises are located to engage the rectangular section of the end box with the fuel element center line parallel to the lengthwise feed of the milling machine. The over-all length of the element is measured with a 36-in. vernier caliper. If necessary, the ends of the end box are faced off with a 4-in.-side mill cutter to the finished element length of 33-5/8 in.

The inlet end box of the stationary fuel element is placed in a drill jig, and the hole for the locating pin is drilled (Alco Drawing R9-13-1003). The pin is then inserted and staked. The retaining hole for the spring on the outlet end box of the element is located, drilled, and counter sunk.

K. Final Inspection

The final inspection of the fuel element is described below:

1. An inspection ring is placed around each end box. Both rings are made with identical outside diameters (~3-1/2 in.) while the inside diameters are made to fit the maximum diameter of the end boxes at the grid location area.

   The rings are positioned on the end boxes and are placed in a pair of matching "V" blocks set on a surface plate. Concentricity is measured with a dial indicator at center-line points "D" and "E", shown on Alco Drawing R9-13-1003, while revolving the rings and element through 180 deg. Maximum variation allowable is 0.002 in. TIR.

2. With the element still positioned in the matching "V" blocks, the perpendicularity of surface "Z" to axis "Y" is measured with a die-maker's square and a feeler gauge. Maximum variation allowable is 0.002 in.

3. The nominal 29-1/4-in. length between shoulders of the end boxes is measured with a 36-in. vernier caliper. The nominal 33-5/8-in. over-all assembly length is also measured in this manner. The tolerance allowed on both lengths is ±0.010 in.

4. Gross distortion and warpage of the completed element are checked by passing the element through a box with inside dimensions of 2.896 in. x 2.896 in. and 35 in. long. The element must pass freely through the box for acceptance.

L. Numbering and Degreasing

Each completed fuel element is identified with the same number that was previously marked near the end of one of the side plates. The number is stamped with a 1/2 -in. stamp on the flat surface of both end boxes.

Subsequent to final machining, the fuel element is cleaned in a vapor degreaser. The element is lowered slowly in a horizontal position into the degreaser, and is allowed to remain in the vapor area until the entire unit is heated. A stream of liquid solvent is directed through the element. After removal, clean air is carefully blown through the assembly to remove any solid debris. The element is allowed to cool in a vertical position to room temperature.

VII. PREPARATION FOR SHIPMENT

In order to minimize fission-product activity in the reactor cooling water, it is necessary to decontaminate the surfaces of all fuel elements prior to shipment. If possible, the decontamination operation should be conducted in an area removed from the fuel fabrication plant and which is relatively free from airborne activity due to fissionable material. All units are to be pickled in warm 10% nitric acid-water solution for 10 min, rinsed in hot running water and dried. Immediately after drying the component shall be wrapped in a heavy dry paper and enclosed in a plastic sheath which must be thermally sealed to protect the component from the ambient atmosphere. The components are then packaged in suitable shipping containers which are designed to protect the units against damage or contamination during shipment and to meet AEC requirements with respect to criticality.

VIII. REFERENCES

The following standards, drawings, and publications form an integral part of this specification:

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2. Alco Drawing R9-13-1003, Fuel Element (Stationary)
3. Alco Drawing B9-13-2007, Fuel Plates (Stationary)
4. Alco Drawing B9-13-2008, Spring (Fuel Element)
5. Alco Drawing D9-13-2014, Side Plate and Comb (Fuel Element Stationary)
6. Alco Drawing C9-13-2022, Fuel Element End Box (Inlet)
7. Alco Drawing C9-13-2023, Fuel Element End Box (Outlet)
8. Alco Drawing A9-13-2024, Dowel (Fuel Element Stationary)
9. Alco Drawing D9-13-2080, Final Machining Jig APPR-1 Fuel Plates (Stationary)
10. ORNL Drawing D-23423, Stationary Fuel Element Braze Jig
11. ORNL Drawing D-27219, Powder Metal Die Assembly

12. ORNL Drawing D-27220, New Stationary Fuel Plate Powder Die

13. ORNL Drawing D-28950, Blanking Die Assembly

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3. A. L. Boch
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