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TECHNOLOGY OF THE HAPO LEAD DIP FUEL ELEMENT CANNING PROCESS

E. A. Weakley
Process Engineering
Engineering Operation

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December 15, 1958

HANFORD ATOMIC PRODUCTS OPERATION
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FOREWORD

This report constitutes a detailed presentation and discussion of the technology of the Al-Si lead dip canning process as it is carried out at HAPO. An attempt has been made to assemble in one document all of the pertinent information accumulated up to the date of issuance of the report, and to indicate areas and programs of current and future development. An extensive bibliography is included. In order to enhance the usefullness of the report, the table of contents has been expanded to provide a ready reference for any particular phase of the process that might be of interest to the reader.

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TECHNOLOGY OF THE HAPO LEAD DIP FUEL ELEMENT CANNING PROCESS

INTRODUCTION

The primary responsibility of the Fuels Preparation Department, General Electric Company, is the fabrication of uranium fuel elements for the Irradiation Processing Department for plutonium production. Since uranium reacts rapidly with water, the uranium must be protected by a water tight jacket which is firmly bonded to the uranium to provide good heat transfer for the heat of fission from the uranium to the reactor coolant water. Besides being water tight under reactor conditions, other requirements are placed on the protective jacket such as (1) high corrosion resistance in water and air, (2) high thermal conductivity, (3) low neutron capture cross section to avoid poisoning affects on the reactors, (4) must be tough to withstand the abrasion of handling and reactor charging, (5) must maintain strength under reactor operating conditions, (6) easily applied on a production basis to give a bonded fuel element assembly, and (7) low cost.

The jacket can be bonded directly to the uranium core (as in co-extrusion cladding) or by a bonding medium such as a braze material or a metallic coating on the uranium. A good bonding medium should meet the following requirements: (1) have high corrosion resistance to serve as a secondary corrosion barrier in the event of a jacket failure, (2) low capture cross-section, (3) high ductility, (4) high thermal conductivity, (5) must form a strong metallurgical bond between uranium and the jacket, (6) should not form intermetallic phases or compounds with uranium or the jacket, (7) should serve as an effective diffusion barrier between the uranium and jacket, (8) easily applied on a production basis, and (9) low cost.

[redacted]

Irradiation imposes severe service requirements on uranium and for optimum service in a reactor, the uranium core must (1) not warp, bump or change dimensions to any great extent, (2) withstand the operating stresses without fracturing, (3) be free of large cracks, seams, and inclusions, (4) have high density, (5) have a uniform reactivity, and (6) be of high purity and free of large amounts of included gasses.

The materials that best meet the above requirements to date at the existing reactor requirements are: (1) aluminum jackets, (2) an aluminum-silicon brazing material, and (3) alpha-rolled salt-bath beta-heat-treated uranium cores. As the reactor operating conditions become more severe, the materials used (as well as the canning methods) must be changed to keep pace with the reactor requirements.

Uranium fuel element cores have been canned in aluminum jacketing components at HAPO by two dip brazing techniques employing aluminum-silicon alloy as the brazing medium; the triple dip process and the lead dip process. The lead dip process, a simpler canning scheme, replaced the triple dip process as the standard fuel element fabrication process in March, 1954. The lead dip process has two principle advantages over the triple dip process: (1) canning costs are lower because fewer operations and less equipment are required, and (2) the structure and properties of the uranium core, which remain in the alpha phase throughout canning, are essentially unchanged permitting the retention of the desirable fuel element core properties that can be obtained during fabrication and heat treatment of the uranium.

The triple dip canning process basically consists of canning uranium cores by the following steps, which heat treat the uranium during the canning operation:

1. Preheating the cores in a bronze bath covered with a flux layer

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2. Quenching the cores in a tin bath which also removes excess bronze from the core surfaces.

3. Centrifuging the cores to remove excess tin.

4. Dipping the cores in an Al-Si bath to remove tin from the core and coat it with Al-Si.

5. Assembling the cores, cans, and caps in an Al-Si bath

6. Water quenching the canned assemblies.

As a comparison, the lead dip canning process basically consists of canning pre-heat treated uranium cores by the following steps:

1. Preheating the cores in the lead layer of a duplex bath, which consists of a lead layer on the bottom and an Al-Si layer on top.

2. Agitating the core in the Al-Si layer of the duplex bath to remove excess lead.

3. Assembling the cores, cans, and caps in an Al-Si canning bath.

4. Water quenching the canned assemblies.

HISTORICAL BACKGROUND

The lead dip canning process was developed in 1944 and 1945 at HAPO but the urgency of production was such that once it was found that the triple dip process would produce satisfactorily canned fuel elements, it was immediately necessary to freeze the canning procedure and concentrate on production.[1] Therefore, development work ceased on the lead dip process until 1947. At that time, fuel elements were starting to blister in the reactors and it was believed that structures developed within the uranium as a result of passing through phase transformations might be conducive to blistering.[2] (Triple dip uranium cores were made from gamma extruded rods and the bronze canning bath transformed the uranium core into the beta phase.) [redacted]

Since the lead dip process operates below the alpha-beta transformation temperature, the development work on the lead dip canning process was resumed using alpha rolled uranium. The lead dip process appeared so promising that in 1948 all production was converted to canning alpha rolled uranium by the lead dip process.[3,4] After about three months of production, it was found that the uranium cores were growing longitudinally during irradiation. The canning of alpha rolled uranium cores by the lead dip process was immediately stopped and the production facilities were converted back to the triple dip process, but using cores from alpha rolled rods.

After 1948, development work on producing a desirable uranium structure prior to canning was carried out. By 1952, a satisfactory heat treating method using a molten chloride or carbonate salt bath was developed and initial production test material was canned by the lead dip process.[5] The lead dip canning process developed in 1952 (and which is nearly the same process as used presently) was essentially the same process used in 1948 except for two moderate changes: (1) the uranium cores are preheated in the duplex bath in the vertical position rather than in the horizontal position and (2) an Al-Si dip bath between the duplex bath and the canning bath was eliminated.

In 1953, a large scale production test (PT 305-105-25-M) was canned using uranium beta-heat-treated in rod form in molten carbonate salt. In March, 1954, the lead dip canning of uranium, salt-bath beta-heat-treated in rod form, was adopted as the standard HAPO fuel element assembly process.[6,7,8]

Since the adoption of the lead dip canning process in March, 1954, three basic types of fuel elements have been canned: (1) solid uranium cylinders, (2) cored (hollow cores with aluminum or uranium end plugs) uranium cylinders and (3) I & E (hollow cores) uranium cylinders. Within these basic types of fuel elements, a large number of different size cores and cores with varying concentrations of U^{235} have been produced.

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The cored uranium fuel element was developed in late 1954, with welded-in uranium end plugs. By mid 1955, cored fuel elements with uranium end plugs were replaced by cored fuel elements with pressed-in aluminum end plugs, which were cheaper and easier to fabricate. The cored fuel element production (which did not get over 15 per cent of the total production for any one month) was discontinued in the latter part of 1957, since the cored fuel elements were not effective in reducing split type reactor failures.

In late 1955, the I & E (Internally and Externally cooled) fuel element was developed for initial reactor testing and in September, 1956, production of I & E fuel elements for large scale reactor testing was started. The production of I & E fuel elements has steadily increased, due to the excellent reactor performance of I & E fuel elements, until by October, 1958, greater than 85 per cent of the fuel elements canned per month were I & E fuel elements.

DISCUSSION

The lead dip canning process has been used exclusively for canning reactor fuel elements at HAPO since March, 1954. The lead dip process replaced the triple dip process which was used almost continuously from 1944 to March, 1954. The lead dip process was developed because it was (1) a cheaper and easier canning process and (2) the uranium core properties were essentially unchanged by the canning operation. This lead dip process has been used for canning three basic types of fuel elements; solid, cored, and I & E fuel elements. The cored element which was developed in 1954, was discontinued in late 1957. The canning of I & E fuel elements, however, has steadily increased since initial development in late 1955 until greater than 85 per cent of the fuel elements canned were I & E pieces. It should be noted that conversion to the I & E fuel element has required an increased product mix to fully realize the capabilities of the I & E concept. Thus, for the eight HAPO reactors, three types of I & E fuel elements are required,

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each differing from the other by slight differences in outside and inside diameter of the finished element. These three types have been designated at HAPO as "C", "K", and "O" size corresponding to the C reactor, the two K reactors, and the five old or original reactors built at HAPO. These dimensional differences result from the necessity to control certain limits on the maximum temperature of the water flowing around the outside of the fuel element and through the inner tube.

In May, 1957, the major process development activities were transferred from the production area (313 Building) to the 306 Building Pilot Plant which greatly accelerated the development programs. Using this facility avoids interference with normal production and provides an uninterrupted effort on development programs. Only after the process developments have proven feasible in the Pilot Plant are they exploited in the production area.

The flow sheet of the lead dip canning process for I & E fuel elements as of October, 1958, is shown in Figure 1. The flow sheet for the solid and cored fuel elements is similar except for changes due to component differences. For example, cored fuel elements require (1) a plugging operation after core pickle inspection and prior to immersion in the duplex bath, and (2) a gamma ray core test at final inspection to detect any leakage of bath metal into the core bore.

A general description of the process follows with a more detailed account of the canning assembly variables that affect the fuel element quality:[6, 7]

I. Components

A. Component Materials

1. Aluminum Components[9, 10]

Two types of aluminum alloy are used for fuel element jackets, at HAPO:

(1) 1245 (C-64) alloy, which is similar to 1100 (2S) alloy but with iron and silicon control, has been used at HAPO since 1944 with few changes in alloy specifications, and

[redacted]

(2) M-388 (X-8001) alloy, which is a one per cent Ni, 0.5 per cent Fe alloy, has been used in production quantities at HAPO since mid 1957. The M-388 alloy was introduced to improve the intergranular corrosion resistance of the jackets. Over-all corrosion rates for M-388 alloy are about the same as C-64 alloy but M-388 alloy inhibits intergranular attack of the jacket at points of high localized temperatures.

The aluminum jackets must be mechanically sound, have an acceptable corrosion rate under operating conditions, and must not absorb an excessive number of neutrons. To assure an acceptable metallurgical structure, the fabrication techniques are specified by FPD to the supplier. The aluminum cans and the I & E cap spires are all impact extruded from rod stock while the solid caps are impact extruded from aluminum plate stock with the extrusion transverse to the metal flow in the blank. The finished aluminum components must be free of serious visual defects, cracks, seams, porosity, laminations, and imbedded foreign material.

The impurity limits for the 1245 (C-64) alloy and the M-388 (X-8001) alloy are:

a. 1245 (C-64) alloy impurity limits:

(1) Iron	0.35 - 0.50%	(9) Tin	0.01%
(2) Silicon	0.17% max.	(10) Lead	0.01% max.
(3) Titanium	0.05% max.	(11) Bismuth	0.01% max.
(4) Copper	0.04% max.	(12) Nickel	0.01% max.
(5) Manganese	0.03% max.	(13) Lithium	0.008% max.
(6) Chromium	0.03% max.	(14) Cadmium	0.003% max.
(7) Zinc	0.03% max.	(15) Cobalt	0.001% max.
(8) Magnesium	0.01% max.	(16) Boron	0.001% max.
		(17) Aluminum	balance

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b. M-388 (X-8001) alloy impurity limits:

(1) Nickel	0.9 - 1.3%	(6) Cadmium	0.003% max.
(2) Iron	0.45 - 0.70%	(7) Cobalt	0.001% max.
(3) Silicon	0.17% max.	(8) Boron	0.001% max.
(4) Copper	0.15% max.	(9) Others (each)	0.05% max.
(5) Lithium	0.008% max.	(10) Others (total)	0.15% max.
		(11) Aluminum	balance

The aluminum end plugs for cored fuel elements were fabricated from 1100 (2S) alloy by either punching or machining plate or bar stock and annealing to a dead soft temper after fabrication.

2. Uranium Cores[9]

Critical tests which accurately determine the properties of uranium necessary for optimum reactor service or simulate reactor conditions are not available. Therefore, it is necessary to specify fabricating conditions that give desired properties as demonstrated by reactor performance. In general, uranium is desired that is (1) fine-grained, (2) randomly-oriented, (3) uniform in structure, (4) free from asymetric residual stresses, (5) high in strength and ductility, and (6) free from striations, fabrication defects, inclusions, and voids.

The uranium presently used (up to October, 1958) for standard production of solid, cored, and I & E fuel elements at HAPO is (1) fabricated from ingots with a minimum seven-inch diameter, (2) hot-rolled into rods in the alpha phase such that the finished rods are completely recrystallized, as shown in Figure 2, (3) completely transformed into the beta phase in a carbonate or chloride salt bath in rod form to randomize the orientation of the grains, (4) water quenched into the alpha phase in rod form to give a structure as shown in Figure 3, and (5) machined into finished fuel element cores. The density and impurity limits are closely

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controlled to obtain the best reactivity and structural properties. The minimum density has been established at 18.82 grams per cubic centimeter.

Impurities are known to have some detrimental effects on uranium quality; the impurities may (1) combine with uranium to form second phase inclusions or striations which may act as stress risers, (2) cause difficulty in fabrication, (3) have high thermal neutron absorption cross sections which will cause a decrease in reactivity, (4) form long half-life radioactive isotopes which create separation and disposal problems, and (5) cause extraction difficulties. Composition limits are specified for the impurity elements which are inherent in the current production processes for uranium. These limits are consistant with uranium of high quality at purity levels capable of being maintained by uranium refiners and fabricators. Carbon has both a detrimental inclusion-forming effect and a beneficial grain-refining effect and therefore maximum and minimum limits are specified. The chemical impurities limits that are specified to date are:

Element	Composition Limits
Carbon	150 - 750 ppm
Chromium	65 ppm max.
Iron	150 ppm max.
Magnesium	25 ppm max.
Manganese	25 ppm max.
Nickel	100 ppm max.
Nitrogen	100 ppm max.
Silicon	75 ppm max.

Hydrogen in the form of uranium hydride is also undesirable in uranium since the hydride decomposes at the canning temperatures evolving hydrogen and forming braze porosity. The hydrogen content varies with the hydroxyl content of the heat-treating salt

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which in turn varies with absolute humidity. However, at the present time, it is not possible to set an acceptable limit which can be consistently maintained by the supplier.

3. Steel Sleeves[10]

Steel sleeves are used to protect the aluminum cans from mechanical damage and from attack on the outside surfaces of the can by molten Al-Si during the assembly and quenching of the fuel elements.

The steel sleeves used for lead dip canning should (1) not distort appreciably during the canning operation, (2) not be capable of entrapping moisture, (3) be free of defects that might allow Al-Si to contact the outer surface of the aluminum can, and (4) not contain any contaminate that will be transferred onto or into the aluminum jacket.

The steel sleeves presently used are fabricated from commercial SAE 1030 steel seamless tubing and plate stock with a carbon content of 0.28 to 0.33 per cent.

B. Component Dimensions

The dimensions of the lead dip canned uranium fuel element presently fabricated or to be fabricated in the near future at HAPO by FPD are shown in Figure 4. The components used to produce this variety of fuel elements are shown in Figures 5 and 6. The cored fuel elements are not included since they have been discontinued, but a sketch of the two principle canned natural uranium cored fuel elements is shown in Figure 7.

1. Dimensional Changes Due to Reactor Requirements

a. I & E Fuel Elements

Several dimensional changes have been made in "C", "K", and "O" size I & E fuel elements, both natural and 0.94 per cent enriched uranium. Original dimensions were established based on calculations of required water flow to give equal temperature

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rise in the annulus and inner tube and on out-of-reactor flow tests. Subsequent adjustments have been made to alleviate problems that have arisen during actual irradiation. These changes have been made to minimize the top-of-the-annulus water temperature in the reactor flow tubes. This high top-of-the-annulus water temperature occurs since the I & E pieces have a larger diameter than solid elements and therefore rest in an eccentric position in the process tube. It is possible to reduce this temperature rise to a more tolerable range by (1) reducing rib height, (2) use of a water mixing device in the fuel element column, and (3) reducing the fuel element outer diameter.[11] Reducing the rib height would prevent the use of solid fuel elements in those particular tubes and would result in a large loss of production time during the rib reducing operation. A mixing device (See Figure 8) has been used but there is a reactivity loss and a problem in coolant monitoring with these pieces. The most attractive approach was to change the dimensions of the I & E fuel elements. This was done as shown below:

(1) "C" size normal uranium I & E:

(a) Can O.D. from 1.474 to 1.460 ± 0.002 inches.

(b) Nominal can wall from 0.045 to 0.040 inches.

(c) Core O.D. unchanged at $1.370 \begin{smallmatrix} +0.001 \\ -0.002 \end{smallmatrix}$ inches.

(d) Core I.D. unchanged at 0.481 ± 0.007 inches.

(e) Spire I.D. unchanged at 0.375 ± 0.003 inches.

(2) "C" size 0.94 per cent enriched uranium I & E:

(a) Can O.D. from 1.474 to 1.454 ± 0.002 inches.

(b) Nominal can wall from 0.045 to 0.038 inches.

(c) Core O.D., core I.D. & spire I.D. unchanged as in (1) above.

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(3) "K" size normal uranium I & E:

(a) Can O.D. from 1.498 to 1.474 inches, and finally to 1.460 ± 0.002 inches.

(b) Nominal can wall from 0.045 to 0.040 inch.

(c) Core O.D. from 1.394 to 1.385 inches, and finally to $1.370^{+0.001}_{-0.002}$ inches.

(d) Core I.D. from 0.466 to 0.481 inches, and finally to 0.491 ± 0.007 inches.

(e) Spire I.D. from 0.360 to 0.375 inches, and finally to 0.385 ± 0.003 inches.

(4) "K" size 0.94 per cent enriched uranium I & E:

(a) Can O.D. from 1.474 to 1.454 ± 0.002 inches.

(b) Nominal can wall from 0.045 to 0.038 inches.

(c) Core O.D. unchanged from $1.370^{+0.001}_{-0.002}$ inches.

(d) Core I.D. from 0.481 to 0.506 ± 0.007 inches.

(e) Spire I.D. from 0.375 to 0.400 ± 0.003 inches.

(5) "O" size normal uranium I & E:

(a) Can O.D. from 1.460 to 1.445 ± 0.002 inches.

(b) Nominal can wall from 0.045 to 0.040 inches.

(c) Core O.D. unchanged from $1.356^{+0.001}_{-0.002}$ inches.

(d) Core I.D. unchanged from 0.416 ± 0.007 inches.

(e) Spire I.D. unchanged from 0.310 ± 0.003 inches.

The above dimensional changes resulted in a change in the can I.D.-to-core O.D. gap. This gap (difference in diameters before canning) was reduced from 0.014 inches (nominal) to 0.008 to 0.010 inches.

b. Four-Inch Solid Fuel Elements

Very few four-inch normal uranium solid fuel elements are required at the present time. The ones that are used, however,

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must withstand essentially the same reactor conditions as the thick walled (0.045 inch thick can wall) eight-inch solid fuel elements. The four-inch solid fuel elements used until 1957 were all canned in cans with 0.035 inch thick walls but the present corrosion rates would make the use of these pieces prohibitive. Therefore, the four-inch fuel element dimensions were changed by using a 0.045 inch thick can wall and reducing the core O.D. from 1.356 inches to $1.336^{+0.001}_{-0.002}$ inches.

c. Contoured (Tru-Line) Fuel Elements

A major cause of fuel element failures in the reactors has been corrosion of the aluminum jacket. In many cases, this corrosion is identified by a characteristic film pattern or "hot spot". Metallurgical examination has shown that failures having this type of film pattern normally fail as a result of intergranular corrosion of the aluminum within the "hot spot". It is believed that temperatures of 150 C or greater are required for intergranular attack of 1245 alloy to proceed in reactor process water (over 200 C for M-388 alloy).[12] Fuel element jacket temperatures of this magnitude are not expected to occur unless coolant flow or heat transfer between jacket and core is restricted during irradiation. Coolant flow restrictions may result from fuel element cocking, warping and column bowing.

To partially alleviate fuel element misalignment in reactor process tubes contoured (tru-line) fuel elements were developed. (See Figure 9) The small tru-line contour was fabricated in production test quantities in 1956 but flow laboratory tests indicated that the small tru-line features are only partially effective in preventing misalignment under normal reactor charging conditions and are ineffective under operational charge-discharge (flush charging) conditions.[13] The blunt-nosed tru-line design

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was then developed and tested in the flow laboratory. The charging showed that blunt-nosed tru-line fuel elements will consistently eliminate cocking in columns under severe charging conditions, i.e., flush charging.[13] A large scale production test was written[14] and canning of these elements, using both solid and one-half inch cored uranium cores and M-388 and 1245 aluminum alloy began in mid 1957, and is continuing to date with solid cores.

As soon as the aluminum components for blunt-nosed tru-line pieces were exhausted, this tru-line feature was replaced by the standardized tru-line fuel element. The standardized tru-line feature will save set-up time on the facing lathes in converting from I & E to solid tru-line fuel elements. This standardized tru-line feature is essentially the same for I & E and solid pieces as shown in Figure 4. The standardized tru-line was tested in the flow laboratory and was found to be as good as the blunt-nosed tru-line feature.[15]

The I & E fuel element contour design was changed only slightly when converting from the initial to the standardized tru-line feature (as shown in Figure 10), in September, 1957.

2. Dimensional Changes Due to Fuels Preparation Requirements

a. Component Assembly Tolerances Prior to Canning

(1) Spire-Core Annulus

The initial difference in spire O.D. and core I.D. was a nominal 0.016 inch with tolerances in the spire O.D. of ±0.002 inch and on the core I.D. of ±0.003 inch. In September, 1957, the tolerances in the core I.D. were relaxed to ±0.007 inch, with the nominal 0.016 inch gap unchanged. This relaxation is expected to save about three cents per pound on the fabrication costs due to less scrap recycle.[16]

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(2) Cap-Can Annulus

The initial dimensions of the solid cap O.D. and can I.D. were such that an interference fit resulted between these components prior to canning, e.g., can I.D. was 1.345 to 1.351 inches and cap O.D. was 1.345 to 1.350 inches. When the canning baths were operated using a silicon concentration in the 10.5 to 10.8 per cent range and a temperature below 592 C, it was found that it was necessary to excessively swirl the solid caps in order to prevent an excessive number of high cap rejects.[17] By reducing the cap O.D. 0.005 inch, no swirling in the canning pot was necessary, the high cap rejects were low, and the average braze line width was only 0.016 inch. Therefore, the solid cap O.D. was reduced 0.005 inch on all component orders.

The I & E cap O.D. - can I.D. dimensions were also an interference fit when first developed,[18] but the cap O.D. has since been reduced 0.005 inch in order to reduce the high cap reject rate and make it easier to assemble the components.

(3) Can-Sleeve Annulus

The can O.D. to sleeve I.D. dimensional tolerances have been established by canning experience since 1944. The present nominal difference between the can O.D. and sleeve I.D. is 0.0125 inch with a tolerance of ±0.0015 inch on the sleeve I.D. and ±0.002 on the can O.D. If the difference in dimensions is not large enough, the aluminum can wall will buckle due to its greater coefficient of thermal expansion than the steel sleeve and will result in a canning reject. If the difference in dimensions is too large, Al-Si will flow down the annulus between the can and sleeve resulting in reject fuel elements. To reduce the tendency of Al-Si to flow down

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between the can and sleeve, two grooves were added to the can O.D. as shown in Figure 5, in about 1952. These grooves form a seal between the can and sleeve by thermal expansion.

(4) Core Eccentricity

The I & E core eccentricity limit was relaxed from ±0.005 inch to ±0.008 inch in January, 1958.[19] This relaxation is expected to save up to three cents per pound in fabrication costs due to less scrap recycle.[16]

b. Core Surface Roughness

Prior to late 1953 all of the fuel elements had a special machined surface of about 1,000 RMS (root mean square) applied to the core O.D. as shown in Figure 11. Tests were made on centerless ground cores with the following observations: (1) there was no apparent difference in compound layer strength, (2) the cores are easier to inspect visually for core defects, and (3) the machining operation at the supplier is simplified. In late 1953, the core surface was converted from a 1,000 RMS to a centerless ground surface and in 1955 from a centerless ground surface to an as-machined surface. This as-machined surface simplified the machining operations even further. The present surfaces appear as shown in Figure 12. Some centerless ground cores are still received from the supplier. These pieces are cores that were slightly oversize after machining and are brought into specification by centerless grinding.

Recovered cores are roughened by chemical attack, but there is no detrimental effect on canned quality. In face, the bonds appear to be slightly better than average[20] and the braze porosity is less than in once canned fuel elements.

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c. I & E Can Base Design

The first I & E cans used in any quantity had stepped can recesses as shown in Figure 13-A. In August, 1957, the can base recess was changed to a tapered recess as shown in Figure 13-B. This change was made after destructive examination of several wrinkled spires disclosed that the spire base had gouged into the step in the can recess and may have been responsible for producing wrinkles.[21] A five degree taper was added from the recess to the can wall as shown in Figure 13-C, in late 1957. This change was made for ease in component fabrication during impact extrusion and to reduce lubricant entrapment in the can base during fabrication.

d. I & E Cap-Spire Design

The first cap-spire design used is shown in Figure 14-A. When this design was used, braze-line rejects, such as large voids and impurities were quite high. To reduce the braze-line problems, a reservoir was made in the cap at HAPO as shown in Figure 14-B. This reservoir design was later changed to a hemispherical shape for ease in fabrication by the supplier as shown in Figures 14-C and 5.

In late 1957, a high-boss cap-spire design as shown in Figures 5 and 14-D was made to reduce the amount of Al-Si extending past the O.D. of the canned assembly. This would allow the as-canned pieces to be handled on "skate-wheel" conveyors from the quench tank to the facing lathes. When the first experimental cap-spires of this design were canned, they were found to have less tendency to float after assembly than the standard cap-spires. This should help reduce the number of high cap rejects. Large scale use of this cap-spire design is not expected until early 1959.

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C. Component Life

1. Uranium Cores

Uranium cores from fuel elements that have not passed the inspection standards are recovered and recanned. The aluminum jacket is removed in a boiling caustic solution (14 to 20 per cent NaOH, 10 to 15 per cent $NaNO_3$). This is followed by a 50 per cent NaOH solution at 150 to 170 C to remove the compound layers from the uranium cores. See Section VI for further information.

The canning and recovery cycle removes uranium from the core and each core that has been recovered more than once is weighed individually. Minimum weight standards have been established on each type of fuel element core to prevent excessive loss of reactivity in the reactors. Most uranium cores can be recovered at least three times before they are rejected for being underweight.

2. Steel Sleeves

Steel sleeves are grouped into lots (about 1200 sleeves per lot) when they arrive from the supplier. Each lot is identified and is kept intact during the canning operation, except for obvious reject sleeves. When the fuel element reject rate attributable to sleeve defects becomes economically unfavorable the entire sleeve lot is rejected and a new lot is put into use. With the present SAE 1030 steel sleeves about 150 cycles are obtained per sleeve lot. In the past, SAE 1010, 1015 and 1020 steel sleeves were also used but the cycle life per lot was usually under 100 cycles.

D. Component Development Programs

At the present time one of the major reactor problems associated with fuel elements is the incidence of failures due to "hot spots". This type of failure is due to excessive corrosion of the jacket at the site of the "hot spot". "Hot spots" are areas on the fuel element surface where the uranium core heat is apparently inadequately or nonuniformly removed by the reactor coolant water.

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The primary fuel element factors which may contribute to these "hot spot" corrosion failures are (1) uranium distortion(which causes the fuel element to warp in the process tube and thus restricts water flow) and/or (2) imperfect braze or bond caused by gas porosity non-wet areas, or cracked bonding layers. The M-388 aluminum alloy, which was developed for its superior intergrannular corrosion resistance, has not performed as satisfactorily as expected. This may be due to a lack of optimum fabrication control and methods.

Adverse reactor conditions, such as fuel element misalignment and column bowing, also contribute to "hot spot" corrosion failures. Therefore, the solution to the corrosion failure problem must be achieved by improvements in reactor conditions together with improvements in fuel element fabrication.

The present component development programs are primarily concerned with (1) reducing the tendency of the uranium core to distort and (2) obtaining maximum corrosion resistance for any particular aluminum alloy.

1. Aluminum Components

Fabrication techniques for any given aluminum alloy are known to influence the corrosion resistance of that alloy. Promising alloys currently being developed have not been studied for optimum fabricating techniques and thus improvements in corrosion characteristics may be obtained for these alloys. Also, cheaper and better methods of fabrication of certain component shapes may be possible.

Specific programs now being considered or developed are:

a. Uniform and Homogenous Alloys

Improved processing methods are under development with suppliers to assure that aluminum jacketing components are of uniform and homogenous alloy composition. Specifically this

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applies to the M-388 (1.0 per cent Ni, 0.5 per cent Fe) and A-2 (1.0 per cent Ni, 0.5 per cent Fe, 0.1 per cent Ti) alloys.[22]

b. Cast Extrusion Blanks

Direct casting of extrusion blanks is being tested to determine whether this will result in a more uniform and desirable structure in the finished component and whether the corrosion resistance of the particular alloy is improved.[22]

c. Cast Solid Caps

The feasibility of direct casting solid caps to the proper dimensions is being determined.

d. Al-Si Clad Components

Methods of improving and reducing the cost of fabricating Al-Si clad I & E cap-spires are being studied. Also, the feasibility of producing internally Al-Si clad cans is being determined. Al-Si cladding eliminates aluminum jacket non-wetting in the canning bath, but would increase the cap-spire cost by about 30 per cent.

e. Extruded Closed Cap-Spire

The feasibility of impact extruding a closed cap-spire in one operation is being tested. This would eliminate the separate spire closing operation now required. The present spire closing operation consists of: (1) cutting to length and spinning the tube closed, and (2) machining the tube O.D. to size near the spire tip.

f. Can-Spire Components

A one piece can-spire component with a simple cap (Figure 15) has been developed.[23] These components are used in a simpler I & E fuel element canning technique which is under development. See Section IV, E, 10.

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2. Uranium Cores

Non-optimum heat treatment or fabrication of uranium cores may result in adverse metallurgical orientation or residual stresses. These adverse properties may result in core warping during irradiation causing the fuel element surfaces to touch or nearly touch the process tube. This could result in serious localized overheating resulting in a "hot spot" corrosion failure.

Uranium cores are also known to contain hydrogen that is evolved during canning and can result in gross braze layer porosity. These large braze voids are also possible sources of "hot spot" corrosion failures.

Optimum heat treating and fabricating methods are being developed to produce the most dimensionally stable uranium structure possible under irradiation with the lowest possible hydrogen content. Also, cheaper and easier methods of fabrication are being developed.

Specific programs now being considered or developed are:

a. Delayed Quench.

A large scale reactor test is being made to determine whether a delayed quench in the beta heat treatment of uranium will reduce fuel element warping during irradiation.[22]

b. Core Blank Heat Treating

Past large scale production experience with solid uranium cores showed that individually heat treated cores were more resistant to warp than cores from heat treated rods. This could be due partly to the Medart rod straightening operation now performed after rod heat treating. A return back to an individually heat treated core blank is now being made for production cores to determine if this will reduce warp.[22]

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c. Carbonate vs. Chloride Salt Bath

A reduction of hydrogen in the uranium core by converting from the present lithium-potassium carbonate to a sodium-potassium chloride salt-bath heat treatment is being made for all production cores. All of the uranium heat treated in the chloride salt will be in core blank form. There is a direct relationship between hydroxyl ion content in the carbonate bath to the hydrogen content in the uranium and the hydroxyl ion content varies with the absolute humidity.[24] In general, it was found at NLO that ingot uranium picked up about one to one and one-half parts per million during heat treatment in the carbonate bath but did not pick up hydrogen during chloride heat treatment.[25]

d. Recrystallizing Anneal

An alpha anneal (recrystallizing) treatment following beta heat treatment is being investigated to determine whether this method will reduce fuel element warp during irradiation.[22]

e. New Quenching Methods

The effects after heat treating of quenching rate, media, and temperature on residual stresses in the canned uranium core and their effect on core warp during irradiation is being determined.[22]

f. Cast I & E Cores

Determination of whether directly cast (static and centrifugal) I & E uranium cores from induction and arc melted uranium will show better dimensional stability during irradiation than the presently used wrought cores is being made.[22]

g. Dingot Uranium Cores

Dingot uranium cores have been canned and irradiated in development quantities at HAPO since November, 1955. The

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early dingot cores received had a high hydrogen content and gross porosity resulted from using these cores (See Figure 16). The hydrogen problem has been reduced somewhat, but further reduction is being made. The dingot uranium also has a larger grain size than ingot uranium. In the standard ingot process, uranium metal formed during the reduction of UF_6 is molded into an approximate 300 pound shape called a derby. Derbies are subsequently remelted in a vacuum and cast into seven-inch diameter ingots which are fed to the rolling mill and rolled into rods. In the dingot process, uranium formed during the reduction of UF_6 is molded directly into an approximate 3300 pound dingot which is subsequently forged or extruded into a shape which can be fed to the rolling mill. Dingot uranium is generally purer and has a lower carbon content than ingot uranium. To date dingot uranium also has a higher hydrogen content than ingot uranium.

Dingot cores are still being canned to further establish the irradiation behavior of dingot cores. Methods to reduce the dingot uranium grain size are also being developed.[22]

h. Effect of Uranium Impurities

Evaluation of the effect of increased quantities of impurities in the uranium core on reactor performance is being investigated. This specifically includes increased quantities of iron, manganese, chromium, nickel, silicon and carbon content in both ingot and dingot uranium. The increased quantities considered are in the parts per million range and are not intended to produce alloying effects.[22] If uranium of increased impurity content can be used, a reduction in fabrication cost can be obtained.

i. Effect of Ore Impurities

The effects of rare earth and heavy metals that may be present in new ores coming into the feed metal streams on uranium core fabrication, canning, irradiation, and separation are being determined.[22] [redacted]

j. Alpha Extruded Rods

Development of alpha phase extrusion of uranium rods is continuing. Alpha extruded cores were canned and irradiated at HAPO in 1955 and 1956. Also, small quantities of alpha extruded cores were canned in 1957. Further irradiation of this material as solid cores will be done to determine the warp characteristics.

k. Core Surface Condition

Uranium cores with various surface treatments, such as threading or sand blasting, are being obtained for studies in improving the uranium to Al-Si bond. See Section IV, E, 1.

l. Tru-Line Cores

A tru-line solid and I & E uranium core has been designed for use with a standardized tru-line fuel element (See Figure 17). This design will add about 0.160 inch more uranium per fuel element or about six inches and five inches more uranium per tube in the K and other reactors respectively. The male end of the core is not contoured since there would not be enough gain in conversion ratio and reactivity to warrant the extra machining cost. Of course, new aluminum caps and cap-spires would be required with contoured uranium cores.

3. Steel Sleeves

Steel sleeve development is primarily concerned with extending the sleeve life, a reduction in the inclusion problem, and a cheaper sleeve. There are presently two specific programs on sleeve development:

a. Bottomless Sleeves

Bottomless I & E steel sleeves are now under development. These sleeve are expected to have a longer sleeve life since there is expected to be less distortion during canning than with the

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welded-in bottom sleeves. Sleeve costs will also be less. The inclusion problem due to impurities being lodged in the sleeve during sleeve cleaning is expected to be less since the bottomless sleeves can be cleaned and rinsed more thoroughly than present sleeves. Thin aluminum wafers are to be used in the bottomless sleeves to prevent Al-Si from adhering to the aluminum can. The heat transfer rate to the can base will also be increased.

b. Cheaper Materials

Cheaper materials than the present SAE 1030 steel are being investigated. It may be possible to develop a sleeve that is cheap enough to use only once. This would eliminate the caustic cleaning. Both metallic and non-metallic materials are being investigated.

II. Bare Component Inspection

A. Aluminum Cans[26]

All of the aluminum cans of the same design and alloy within a shipment are grouped into one can lot. This can lot is then inspected statistically to assure an acceptable quality level. An example of acceptance sampling for a lot of 100,000 cans is shown in Figure 18. If the lot is determined unacceptable, 100 per cent inspection is required to remove the defective cans.

B. Aluminum Cap-Spires[26]

All of the aluminum cap-spires of the same design and alloy within a shipment are grouped into one cap-spire lot. This cap-spire lot is then inspected statistically to assure an acceptable quality level. An example of acceptance sampling for a lot of 100,000 cap-spires is shown in Figure 19. If the lot is determined unacceptable, 100 per cent inspection is required to remove the defective cap-spires.

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C. Uranium Cores

1. Acceptance Inspection

All of the uranium cores of the same design and enrichment level within a shipment are grouped into one core lot. This core lot is then inspected statistically to assure an acceptable quality level. An example of acceptance sampling for a lot of 5,060 natural uranium I & E cores is shown in Figure 20. If the lot is determined unacceptable, 100 per cent inspection is required to remove the defective cores.

Recovered uranium cores of the same design and enrichment level are also grouped into lots and inspected satistically to assure an acceptable quality level. Only three inspections are made on recovered fuel cores:

a. Weight

All recovered cores in a lot that have been recovered more than once are weighed to assure sufficient reactivity in any lot.

b. Warp

The statistical sample pieces are measured for warp. Cores over 0.040 inch double throw warp are rejected to prevent non-seating and gouging of the aluminum can during the assembly operation.

c. Visual

The statistical sample pieces are inspected visually for unremoved compound layer and obvious metal defects, such as cracks and splits. All reject bare cores, except recovered cores with compound layer remaining, are returned to the uranium fabricator for remelting and refabricating. Recovered cores with compound layer are recycled through the recovery operation.

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2. Transformation Test [27]

After rolling in the high alpha phase temperature range, the uranium rods from which the fuel element cores are machined are heat treated to randomize the grain orientation. The heat treatment consists of heating the uranium into the beta phase in a carbonate salt bath (approximately 725 C for 12 minutes) and quenching in water back to the alpha phase. The uranium is then said to be "transformed". Untransformed cores (particularly partially-transformed cores) are markedly more dimensionally unstable under irradiation than properly heat treated material.

An ultrasonic test device has been developed to check for the completeness of transformation. This test is based on the equipment discriminating between the average grain size characteristic of untransformed metal (Figure 2) and the larger average grain size typical of heat treated material (Figure 3). High frequency ultrasonic pulses of very short duration are sent through the core to a receiver. The decrease in intensity of the received pulses is a function of the average grain size of the uranium; large-grained uranium decreases the intensity of the ultasonic pulses a greater amount than does fine-grained uranium. The transformation tester is set to reject any core containing untransformed material. At this setting, some cores that are completely transformed but which have abnormally fine average grain size (usually due to impurities) are also rejected.

The ultrasonic transformation rejects, real or spurious, are re-heat treated in a chloride salt bath at HAPO under closely controlled conditions that will assure that the cores are completely transformed. These re-heat treated cores, which are grouped in special lots, are not re-tested on the ultrasonic transformation tester before canning.

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The first transformation testers used for routine production in 1954 were manual load-unload. The present testers (See figure 21) are automatic load-unload machines which require the operator to place the cores in a loading chute and remove the cores from the unload position as shown.

D. Steel Sleeves

All of the steel sleeves of the same design and alloy within one shipment are grouped into one sleeve lot. This sleeve lot is then inspected statistically to assure an acceptable quality level. An example of acceptance sampling for a lot of 1,200 sleeves is shown in Figure 22. If the lot is determined unacceptable, 100 per cent inspection is required to remove the defective sleeves.

E. Bare Component Inspection Development Programs

The bare component inspection is made to detect components that may be reactor failure prone or that will cause difficulty in canning. The primary component inspection development programs are directed toward the development of nondestructive testing equipment to detect abnormal uranium and aluminum structures prior to canning.

1. Aluminum Can Test[22]

Present aluminum cans are generally of uniformly high quality. Furthermore, most, if not all, possible defects are detectable by tests or inspections of the assembled elements. Therefore, there are no plans for developing a production line can test for 100 per cent use.

However, there is a need for a spot test which can be used on bare can lots when suspected can defects are revealed after canning. The type of defects that are expected to be revealed are nickel segregation in M-388 and A-2 alloys and seam defects.

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An experimental electromagnetic can tester is now being used to examine cans from a lot of 125,000 cans which had several (15 out of 3,000 cans) can defects. These defects were seams that were detected after the brazing operation.

2. Uranium Core Tests[22]

a. Transformation Test

The ultrasonic attenuation measurement of grain size is currently applied to all production cores to insure that they have received the proper beta heat treatment. Moderate amounts of continuing development are required to resolve minor operating problems and to optimize the equipment for testing fine grained (but properly heat treated) uranium cores.

Methods for testing cast uranium are also under development.

b. New Ultrasonic Attenuation Test

A new ultrasonic attenuation tester, now in the advanced prototype stage, is being evaluated as a replacement for the present transformation tester and as a laboratory tool for fuel development studies. This unit can not only detect an abnormally small average grain size as does the present transformation tester but is designed also to detect a large average grain size as well as any abrupt discontinuities in attenuation which may be indicative of stress centers.

The new tester is being evaluated under production conditions with various types of uranium cores.

c. Sonic Orientation Resonance Test (SORT)

This test is a resonant vibration method for measuring grain orientation in solid or I & E uranium cores. It has potential value as a replacement for or supplement to the transformation test and as a laboratory tool. Development of a prototype

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automatic tester has been completed and satisfactory operation has been demonstrated in the laboratory. Some small scale experiments have shown this test to be more sensitive for detecting small untransformed areas than the present ultrasonic test. Comparisons have been made between SORT readings and calculated growth indices based on X-ray diffraction measurement. However, as-rolled and heat treated cores giving extreme SORT values did not show corresponding X-ray differences.

No strong case has yet been developed for applying SORT to production use. It is unlikely that any cores with excessive preferred grain orientation are now going to the reactors. This test method also poses more difficult operating problems for production use than do the ultrasonic methods. Further study of this method is planned to define more adequately its capabilities and value.

d. Ultrasonic Surface Inspection Test

This test provides a more sensitive and reproducible inspection for surface and sub-surface seams and striations than is obtained with the present visual pickle inspection. Other surface abnormalities such as dents or inclusions are not detected. The test is capable of grading uranium cores by indicating the total length of defects deeper than some set acceptable depth. This should be an improvement over the present visual inspection. It will also be a tool for better defining the required surface quality and for investigating problems such as the relation between quality and braze porosity.

Laboratory development of a prototype automatic electronic unit has been completed. As soon as the accompanying automatic load-unload mechanical system is completed in about February, 1959, the tester will be evaluated for production use on various types of uranium cores. This ultrasonic surface inspection test is being combined in one tank with the new ultrasonic attenuation test. [redacted]

III. Component Preparation

A. Aluminum Components

The aluminum components must be cleaned and deoxidized so they can be completely wet in the Al-Si canning bath. Wetting of the aluminum components by the Al-Si is essential because of heat transfer consideration in the reactors. The component preparation method used should not alter significantly the dimensions of the caps and cans, lower the reactivity, or decrease the corrosion resistance of the canned fuel element. The present aluminum component preparation method for the production facility is shown in the flowsheet in Figure 23.

Prior to 1956, the aluminum components were cleaned in a manual cleaning line. The manual line was replaced by an automatic machine in 1956. This machine requires operators to load and unload the aluminum components only. (See Figure 24)

The automatic cleaning machines (cap and can, sleeve cleaning, and fuel element etch machines) as purchased contained many parts of brass which were in sliding contact with one another or with other parts. Particles of brass wearing from these sliding surfaces have been a contributing source of copper type inclusions in the finished fuel elements ever since these machines were installed. To reduce this inclusion problem, the brass was replaced on all of the cleaning machines with less harmful materials such as laminated phenolic, stainless steel, Rulon plastic, and carbon steel.[28]

The extrusion lubricant used on aluminum components was removed by the vendor until early 1957. After that time the aluminum cans were received at HAPO uncleaned. A cleaning problem arose when the I & E components and the M-388 components were cleaned in the automatic machines. More lubricant was necessary during fabrication to prevent galling of the I & E cans and a different lubricant was

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needed for I & E caps and M-388 components which are more difficult to extrude. This new lubricant was Houghton's Cyl-Tal which has a tallow base that is more difficult to remove than the wax base used in the previous lubricant (Johnson's #150 Wax-Draw).

The best lubricant removal method found was an immersion degrease in boiling trichloroethylene.[29] It is impossible to immerse the components in boiling trichloroethylene without extensive equipment modification to the automatic machines. The degreasers, however, were converted from a cold spray-vapor degrease cycle to a boiling spray-cold spray-vapor cycle in mid 1957.[30] This has greatly improved the cleaning efficiency of the automatic machines but difficulty in cleaning still arises when M-388 components with an extra heavy layer of lubricant are used.

Before the automatic aluminum cleaning machine degreasers were improved, it was necessary to clean the I & E components in a manual cleaning line. This manual line had a vapor degreaser only and the excess lubricant was removed in a five per cent sodium hydroxide etch at 50 C for two minutes. This was followed by the normal water rinses and Diversey 514 etch.[21] After the automatic cleaning machine degreaser was improved, this sodium hydroxide process was discontinued.[31]

Prior to mid 1953, the etch used to deoxidize aluminum components was either 20 per cent phosphoric acid or one per cent hydrofluosilicic acid. Since phosphoric acid can form a thin inert phosphate coating on aluminum under certain conditions[32] and hydrofluosilicic acid is hard to handle, an investigation was made to find a better etchant for aluminum components.[33] This investigation, followed by a production test, resulted in the adoption of Diversey 514, as the standard aluminum deoxidizer.[34]

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Substitutes for the methanol dehydration have been tried several times without success. Methanol has a fairly low flash point (54 C) and is considered a fire hazard. The latest attempt was to use deionized water to replace methanol but it was found to be inferior to methanol.[35]

The maximum holding time before using the aluminum components is four hours. This time is controlled to prevent using components with a heavy oxide coating which can prevent proper Al-Si wetting. Components held longer than four hours can be recleaned.

B. Uranium Cores

The uranium cores must be cleaned and deoxidized so they can be completely wet in the canning baths to form a metallurgical bond with the Al-Si brazing material. Good bonding is essential to assure proper heat transfer from the uranium core to the cooling water in the reactors. The method of cleaning the uranium cores should not appreciably alter the dimensions of the core or lower the reactivity of the core. The present uranium core preparation method for the production facilities is shown in the flowsheet in Figure 25.

In mid 1955, automatic etching machines, which required loading and unloading baskets only, replaced the manual etch line. This machine, as-received, had a hot nitric spray unit for etching the cores. Under normal production rates the etch machine would not produce satisfactorily etched cores. The cores were reoxidizing at at such a rapid rate that numerous cores had to be re-etched with consequent interruptions to the canning operation. The reoxidation rate was found to be dependent on the amount of oxide removed in the etch operation, the drying temperature in the etch machine, and atmospheric conditions. It was found that (1) dip etching removes four or five times more oxide per unit time than the spray machine process.[36] (2) an excessive loss of acid results when using a spray etch, (3) a minimum of 0.0001 inch of uranium must be removed to prevent rapid reoxidation, and (4) there is no satisfactory catalysts for spray etching.[37]

[redacted]

As a result of the above findings, the automatic etch machines were converted to a dip etch process in mid 1957. A view of the front part of the etch machines and the basket conveyor system is shown in Figure 26.

During the severe braze porosity problem in canned fuel elements that occurred in 1954, tests were made to determine if core preparation had any effect on braze porosity. It was concluded, however, that there was no effect on braze porosity with normal contacts with trichloroethylene, nitric acid (up to a four minute, 15 second etch), or water during the core etching operation.[38]

Immediately following the core etch operation, the cores are in the best condition for visually inspecting the surface. Cores with cracks, seams, folds, or stringers of non-metallic inclusions are rejected since these defects indicate unsound metal that may not withstand the stresses during irradiation. Some small defects however, are permitted, such as follows:

1. External cylindrical surface:
   a. One seam, bottom less than 1/16 inch in depth, and less than two inches long.
   b. One seam, depth unknown, and less than 1/2 inch long.
   c. Five seams, depth unknown, and less than 1/4 inch long.
   d. Light striations.
   e. Marred surface less than 0.063 inch in depth.
2. Internal cylindrical surface: light striations only.

To prevent damage to the can wall during assembly, cores with protrusions greater than 0.003 inch above the core surface or which are sharp to the touch are also rejected.

Cores that are not canned within three hours after canning, those that reoxidize too rapidly, or those that are not cleaned properly are re-etched and canned.

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Etched recovered cores with unremoved compound layer areas are returned to core recovery for reprocessing. All etch reject cores are returned to the uranium fabricator for remelting and refabricating.

C. Steel Sleeves

The steel sleeves which are used to protect the outside surface of the aluminum cans from being wet by molten Al-Si and from mechanical damage during canning and quenching, must be cleaned to remove any foreign particles that might later become imbedded in the can, thus causing difficulty during fuel element welding, or might not be removed during fuel element etch. The sleeve preparation method used should (1) remove all foreign particles from the inside of the sleeve, (2) not leave any deposit on the can that will lower the reactivity of the fuel element, interfere with welding, or not be removed in the final etch, (3) protect the sleeve from rusting in air for at least a week, and (4) protect the sleeve from excessive wetting by molten Al-Si. The present steel sleeve preparation method for the production facility is shown in the flowsheet in Figure 27.

In 1956, automatic sleeve cleaning machines, which required loading and unloading only, replaced the manual sleeve cleaning line. A view of the sleeve load-unload station is shown in Figure 28. There was considerable difficulty with the as-received machines due to copper contamination, insufficient removal of foreign particles from inside the sleeves, and carryover of caustic in the sleeves. The copper contamination and foreign particles resulted in high reject rates for inclusions in the finished fuel elements. The caustic in the sleeves causes a pitting type corrosion of the aluminum can. The copper contamination was reduced by replacing the brass parts on the machines with other materials.[28] Better removal of foreign particles and the reduction of caustic carryover was obtained by (1) improving the first spray rinse after the caustic cleaning bath, (2) converting the second spray rinse after caustic cleaning to a hot

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soap dip, which removes the water insoluble scum formed on the caustic bath surface, and (3) tilting the sleeves to allow them to fill completely with caustic to remove Al-Si chips in the bottoms of the sleeves.[39]

In August, 1958, a 0.4 to 0.6 per cent sodium aluminate solution replaced the 0.5 to 1.5 per cent Ivory soap dip used to coat the sleeves. This coating prevents Al-Si from adhering to the sleeve, acts as a rust inhibitor, and makes it easier to remove the canned fuel element assembly. Soap decomposed in the canning bath forming gasseous compounds that could have caused braze layer porosity in the assembly. Sodium aluminate is nonhydrogenous and does not form gasseous compounds in the canning bath. In addition, sodium aluminate is a better rust inhibitor than soap.[19]

Sleeves are reprocessed if (1) the Al-Si removal is incomplete, (2) not used within seven days, or (3) exhibit condensate or foreign materials.

D. Can-Sleeve Assembly

The prepared sleeves are conveyed to the cap and can cleaning machines where the cans are inserted into the sleeves. Each can as it is taken from the cleaning machine is inspected visually before being inserted into the sleeve. Any can with an obvious inclusion, void, dent, or large mar is rejected and any unclean cans are recleaned. Sleeves that will not let a prepared can be properly seated against the sleeve bottom by the weight of the can is rejected.

E. Component Delivery

The clean components are delivered to the individual canning lines by an overhead "zig-zag" conveyor system.[40] Cores are delivered to the duplex furnace areas and the spire-caps and can-sleeve assemblies to the canning furnace areas.

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F. Component Preparation Development Programs

1. Aluminum Components

The present cleaning techniques are borderline for removing extrusion lubricants and oxide from aluminum components, especially from M-388 and I & E components. Improvements in cap and can cleaning are being developed to decrease non-wetting incidents and inclusion rejects.

Recently there has been a problem in cap-spire non-wetting. The non-wetting occurs primarily on the wafer O.D. and under the cap wafer. Several reactor failures of seven-inch depleted uranium I & E fuel elements have been attributed to cap non-wetting. Failures have been attributed to a small pinhole or void in the weld bead that allowed water entry to the uranium core.[41] As an immediate solution to the problem, the cap wafer O.D., bottom of the wafer, and about one half-inch of the spire next to the wafer have been etched on a large test basis (24,000 cap-spires) in Aluminux and then sent through the standard cleaning operation. The Aluminux, an inhibited caustic solution, is used in a three to six per cent solution at 65 C for about 3.5 minutes. This removes 0.004 to 0.006 inch of aluminum from the wafer diameter. The etching operation is followed by water rinses, a 5 to 15 per cent nitric acid neutralizer, water rinses, a methanol dip, and forced air dry. A manual cleaning line is being set up to use this etch procedure on all I & E cap-spires until a better cleaning method can be developed. This etch line is expected to be in operation the first part of December 1958.

An improvement in extrusion lubricant removal can be made three ways:

a. Modify the present automatic cleaning machines from a spray-vapor degrease to a hot immersion-vapor degrease. This would be a very costly approach, however, due to the extensive changes required.

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b. Have the aluminum vendors degrease the components. This may cost up to as high as ten cents each for cap and can degreasing.

c. The best approach would be to build a separate immersion-vapor degreasing facility in the 313 Building and use the present automatic machines for alkaline cleaning and oxide removal. By removing the existing spray degreaser from the present cleaning machines, more or larger tanks of an alkaline cleaner or deoxidizer could be used.

Lubricant removal, especially of Cyl-Tal, was found to be aided by an alkaline cleaner wash, either L. H. Butcher Company's NE-6 or Wyandotte's Altrex, in place of the standard Duponal solution after degreasing.[29] Several tests have been made using Altrex and it was found to be superior to Duponal for obtaining an aluminum surface that is wet by Al-Si.[35] Further large scale tests are to be run before adopting Altrex as the standard detergent wash.

An ultrasonic unit was received in July, 1958, and has been used in cap, can, and sleeve cleaning experiments. When used in the Duponal solution the components appeared to be cleaned better, but there was no noticeable improvement in Al-Si wetting. The next large scale test will be run using ultrasonics in the Diversey 514 deoxidizer.

2. Uranium Cores

The present nitric acid etch appears to be adequate for cleaning uranium cores prior to brazing. Two studies are being made on the effect of pickle on brittle bonds. These are:

a. Long pickle times give a rough surface to uranium cores. The effect of this roughened surface is being investigated in relation to bond structure and strength.

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b. Uranium cores are presently pickled in a vertical position. Recently it was found during pickling that more uranium was removed from the cylindrical surface near the core bottom than near the core top. If the cores are preheated in the duplex bath in the same vertical position, the amount of uranium removed may be contributing to brittle bonds. Brittle bonds are usually found near the cap end which is the top end of the core in the duplex bath. However, the vertical relation between core pickle and core preheat is not always the same, since the pickle inspector may invert the core during pickel inspection. This may have some bearing on the randomness that occurs in the brittle bond problem.

A study is to be made on whether pickle position effects brittle bonding.

3. Steel Sleeves

Present development programs in sleeve cleaning are directed toward reducing inclusions and improving sleeve cleaning.

Bottomless I & E steel sleeves would make the sleeves easier to clean and also reduce the inclusion problem (See Section I, D, 3). A cheap disposable sleeve, if developed, would eliminate the sleeve cleaning operation.

IV. Fuel Element Brazing

The lead dip process for dip brazing uranium fuel elements requires the use of two molten metal baths. The first, the duplex bath, consists of a layer of aluminum-silicon alloy floated on a layer of lead. The duplex bath serves to raise the temperature of the core to the canning temperature and to wet the core surface with the Al-Si brazing alloy. The second, the canning bath, consists of an aluminum-silicon alloy. The canning bath is used to preheat the jacketing components, to wet the jacketing component surfaces with the Al-Si brazing alloy, and serves as an assembly

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medium for the fuel element parts. The assembly of the components is carried out under the bath surface to exclude air from the assembly. A cold water quench following the canning bath assembly completes the dip brazing operation. The present dip brazing method for the production facility is shown in the flowsheet in Figure 29 and an over-all view of one of the six brazing or canning lines is shown in Figure 30.

All of the transfer and assembly operations in the fuel element brazing operation are done manually. Two attempts were made at HAPO in 1952 through 1954 to develop a mechanized brazing operation.[42, 43] The principle difficulties in mechanization were found to be: (1) inconsistent alignment of equipment during the assembly operation, (2) Al-Si build-up on equipment, and (3) dissolution of equipment in molten Al-Si.

The dip brazing operation is the most important step in the fabrication of lead dip process fuel elements and the quality of the product produced is essentially determined during the brazing operation. Therefore, the process variables in the brazing operation must be closely controlled. The process specifications[6] and standards[7] which define the limits of these process variables have been developed over a long period of time and are continually being modified on the basis of new process knowledge.

In controlling certain variables (such as temperature), optimum conditions are not attained for each quality factor affected by that variable. A compromise must be made between the factors affected to attain the best over-all product quality and yield.

The various phases of the canning operation will be discussed relative to variables and their control. Also major quality factors which are present trouble areas will be discussed along with the status of current efforts now in progress to eliminate or reduce them as a cause of substandard fuel element quality and low yield.

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A. Duplex Bath

The duplex bath consists of a layer of aluminum-silicon alloy (Al-Si) floated on a layer of lead. The lead layer is the preheat medium and the Al-Si layer prewets the core with the brazing alloy. The immersion times, agitation rate, silicon concentration, and temperature are controlled so that cores sent to the canning bath will be approximately at the canning bath temperature, will be coated with braze alloy to prevent core oxidation, and will have a strong ductile Al-Si uranium compound layer formation.

The properties of the intermetallic compounds formed on the surface of the uranium are related primarily to the conditions prevailing during processing in the duplex bath and are not significantly altered by further exposure in the canning bath. The lead reacts with uranium during preheat but the intermetallic compounds formed between lead and uranium are quickly displaced in the Al-Si layer.[44] The resulting intermetallic compounds formed on the uranium core in the Al-Si braze metal have not been positively identified nor has their influence on compound layer strength or ductility been fully determined.

The core is agitated during preheat primarily to increase the heating rate. Agitation is continued in the Al-Si layer to promote wetting and to reduce the amount of lead and interface impurities carried over to the canning bath where they may contaminate the bonding layer of the assembled fuel element. Periodic skimming of dross from the Al-Si surface and the lead-Al-Si interface is necessary to minimize entrainment of impurities in the canned assemblies that might reduce the quality of the brazing layer or result in defective welds.

1. Temperature

The temperature of the duplex bath is controlled by two thermocouples - one extending into the lead layer which controls the power input and the other immersed in the Al-Si to serve as an overtemperature control (See Figure 29). The lead thermocouple

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maintains the temperature.

In early 1958, considerable development work was performed in the fuel element Pilot Plant to optimize temperature in the duplex for the various product types and to improve bond layer ductility.

Temperature control calls for power input into the duplex bath at three ranges - low, intermediate and high. Since the installation of Ajax induction furnaces the control cams have been maintained.

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When cold cores are immersed into the duplex bath the temperature falls below that specified for the operating range before the response system can switch into intermediate or high power to provide adequate power for temperature maintenance. Present work determined that relaxing the control cams and increasing the power tap supplying the intermediate range allows the furnace to operate entirely in the intermediate power range. This method produces less temperature variations in the bath than previously.[45] Thus, power rather than temperature controlling of the duplex bath has provided a better temperature and core preheating uniformity resulting in improved fuel element uniformity. This control measure has been adopted as a production process standard.

2. Agitation and Immersion Time and Agitator and Basket Design

The duplex agitator and basket (Figure 29) are automatically lowered, agitated, and raised by an electro-pneumatic control system which is coordinated with and is a part of the canning cycle. Cores are manually inserted into and removed from the basket using core carrying tongs. After core insertion, the basket drops through the Al-Si layer into the lead and is agitated. Cores are raised into the Al-Si layer and agitated and then raised from the bath for removal. The direction of agitation is nearly perpendicular to the cylindrical surface of the cores, with the cores oriented as shown in Figure 29.

The core basket has recently been modified to hold four cores instead of the previous two. However, only two cores are preheated at the same time leaving two empty core holders. When the basket is raised into the load-unload position, two cold clean

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cores are inserted into the two empty core holders and then the two preheated cores are removed and carried to the canning bath. One man does the loading, unload and core carrying operation where previously it was necessary for a second man to load the empty core holders after the preheated cores were removed. The cast stainless steel core baskets are designed to have as little shielding structure as possible to allow the maximum washing action during agitation.

Conditions are about the same for solid and I & E cores. It may be supposed that heat requirements for the I & E core would be less than that for solid. However, when a cold I & E core passes through the Al-Si layer, Al-Si solidifies on the core surface plugging the bore and must be remelted before internal heating by the molten lead is possible.

3. Bath Composition

The lead layer consists of commercial grade pig lead of ASTM Standards B 29-49. The Al-Si layer is a hypoeutectic melt of aluminum-silicon made from virgin alloy or reclaimed lathe scrap.

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Al-Si made from virgin metal has the following composition:

Aluminum plus silicon	99.0 per cent minimum
Copper	0.10 per cent maximum
Iron	0.50 per cent maximum
Others - each	0.05 per cent maximum
Others - total	0.20 per cent maximum

The normal operating range of silicon in the Al-Si layer and the normal temperature range are shown in Figure 31 with respect to the Al-Si equilibrium diagrams. The silicon concentration of the Al-Si layer is determined at the beginning of each shift and every four hours of operation by a thermal analysis procedure.

The thermal analysis procedure[47] consists of running a cooling curve on a sample of Al-Si and measuring the temperature difference between the liquidus and solidus thermal arrests. With this temperature difference between the liquidus and solidus lines and the Al-Si equilibrium diagram (Figure 31) the per cent silicon content can be determined.

4. Layer Levels

The depths of the lead and Al-Si layers must be such that the cores will be preheated and agitated completely within the particular layer with no part extending into the interface zone.[48] If the top area of the core extends into the Al-Si layer during agitation, the prolonged contact builds up a thick brittle compound layer which is easily fractured by thermal or mechanical shock resulting in a fuel element having poor heat transfer qualities. If the bottom area of the core extends down into the interface while agitating in the Al-Si layer, considerable lead and interface impurities are carried into the canning bath and may contaminate the braze layer of the assembled fuel element.

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One inch of lead cover over the top of the core is a minimum amount to satisfy process requirements. This has been extended recently to three to six inches to eliminate the interface effects on bond brittleness. At least two inches of cover over and under the core in the Al-Si layer is required to prevent bonding and impurity problems in the Al-Si layer. The total depth of the Al-Si layer is 9.5 to 11 inches and the minimum depth of the lead layer is ten inches. The bath level is maintained at a fixed depth of about six inches from the top of the furnace. The Al-Si layer is measured by means of a steel measuring rod with a flat steel base which floats on the surface of the lead.

5. Bath Life and Impurities

The period of bath use is determined by the concentration of soluble impurities that are detrimental to the canning process or appear as quality defects in the canned element. In the early period of lead dip canning, limits were established for concentration of lead in the Al-Si and for uranium in the lead and Al-Si. Continual relaxation of these limits up to the apparent solubility point of the impurities revealed no detectable ill effects. Under current operating conditions the duplex lead or Al-Si layer is not replaced unless an unusual contamination problem arises.

A sample of the Al-Si layer is taken each week for analysis of bath impurities by the Analytical Laboratory. The lead layer is not routinely sampled for impurity analysis. The bath impurities build up rapidly to their saturation value with fluctuations due to dragout and makeup additions.

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All of the undissolved impurities in the duplex bath having a density between that of lead and Al-Si collect and float at the interface layer. These interface particles can reduce the quality of the braze layer or produce a defective weld if they are carried on the core into the canned assembly. Therefore, the interface layer is skimmed with a wire mesh at the beginning of each shift and at intervals of every two hours to remove the large particles. The Al-Si surface is also skimmed frequently (at least every five cycles) to reduce dross carryover into the canning bath and canned assembly.

During the operation of the duplex induction furnaces, a buildup of solid material forms on the walls of the inductor channels. This deposit if not removed periodically will restrict the normal flow of metal through the channel and may damage the furnace. To remove this deposit the channels are broached each day, including weekends, with suitable broaching tools.[47]

This buildup of solid material also occurs on the furnace bottom and walls. To control this buildup the walls are scraped down and the bottom cleaned each weekend.

B. Canning Bath

The canning bath consists of a molten hypoeutectic aluminum-silicon alloy. The bath serves as a medium for preheating and pre-wetting the aluminum jacketing components, provides the brazing alloy

[redacted]

required for the assemblies, and provides a suitable environment for assembly of the components. The silicon concentration, bath temperature, time limits, and assembly method have been established through test and production experience to achieve complete bonding of the component parts with as little dissolution of the jacketing material as possible.

The following operations are carried out in the canning bath:

1. Can-sleeve preheat
2. Can-sleeve submerge
3. Cap preheat
4. Fuel element assembly

The can-sleeve assembly is preheated by immersing the sleeve in the bath to about a one-half inch from the open end. At the end of the preheat period the assembly is submerged allowing the can to fill with molten Al-Si. During the submerge period the can temperature is raised to the ambient bath temperature and wetting of the can with Al-Si is started. The submerged can-sleeve assembly is vibrated to reduce the porosity in the braze layer of the completed assembly.

The cap for solid fuel elements is preheated by submersion in the bath and is aided in being wet by the Al-Si by either: (1) being vibrated, or (2) being removed from the bath, abraided on a Transite board, and re-immersed in the bath. The solid core is carried from the duplex bath, dip-washed in the canning bath, and inserted and seated in the can-sleeve assembly below the bath surface. The prepared cap is then inserted to complete the canned assembly. The canned assembly is removed from the bath and carried to the quench tank.

The I & E cap-spire is preheated by submersion in the bath and vibrated to remove any gas under the cap and to aid in wetting as shown in Figure 32. The I & E core is carried from the duplex bath, dipped in the canning bath, and inserted part way into the can-sleeve assembly.

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The cap-spire is inserted into the core and seated on the core before the top of the core is submerged. The core and cap-spire are seated in the can-sleeve assembly simultaneously. (This technique is shown in Figure 33) The canned assembly is then removed from the bath and carried to the quench tank.

The dross is skimmed from the bath surface, while the can-sleeve assembly is in the submerged position, to minimize the entrainment of dross in the bonding layer.

1. Temperature

The temperature of the canning bath is controlled by two thermocouples - one controls the power input and the other is an over-temperature control. (See Figure 29)

The maximum bath temperature is determined by bath conditions such as silicon concentration and ease of assembly.

If the bath temperature is too high, an excessive amount of can wall will be removed and if it is too low, non-seating of the core and cap will occur.

Temperature control calls for power input into the canning bath at three ranges - low, intermediate, and high.

Under normal operating conditions, the bath temperature often fell below that specified for the operating range before the response system could switch into intermediate or high power to provide adequate power for temperature maintenance. Present work determined that relaxing the control cams and increasing the power tap supplying the intermediate range allows the furnace to operate entirely in the intermediate power range. This method produces less temperature variations in the bath than it had previously.[45] This method also reduces non-seating and gives better cap wetting. This temperature control measure has been adopted as a production process standard.

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2. Bath Composition

The Al-Si bath is a hypoeutectic melt of silicon made from virgin alloy or reclaimed lathe scrap. A maximum nickel concentration is allowed. Higher concentrations of nickel may not be harmful but their effect on the canning process have not been fully determined. Al-Si made from virgin metal has the following composition:

Aluminum plus silicon	99.0 per cent minimum
Copper	0.10 per cent maximum
Iron	0.50 per cent maximum
Others - each	0.50 per cent maximum
Others - total	0.20 per cent maximum

The normal operating range of silicon in the Al-Si and the normal temperature range are shown in Figure 31 with respect to the Al-Si equilibrium diagram. The closer the operating conditions are to the liquidus line the more viscous the melt and the larger the number of non-seat rejects. The further the operating conditions are from the liquidus line the less viscous the melt and the faster the dissolution of the aluminum can and cap. Thus, the operating conditions must be closely adjusted to prevent excessive can wall attack and excessive non-seat rejects.

The silicon concentration of the bath is determined at the beginning of each shift and every four hours of operation by a thermal analysis procedure described previously under IV, A, 3.

In the past the silicon concentration range was tighter and the operating temperature range was higher.

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3. Preheat and Submerge Time

a. Can-Sleeve Preheat and Submerge

The can-sleeve is preheated by immersing the sleeve in the bath with not more than 5/8-inch of the sleeve above the bath surface but high enough to prevent Al-Si from entering the can. If there is too much of the sleeve extending above the bath surface, the top of the can does not reach the canning bath temperature. This makes it difficult to seat the cap resulting in a large number of high caps. If Al-Si falls into the can during preheat, the Al-Si freezes, and must be remelted and brought to the bath temperature before the core will seat in the can. The time needed to remelt the Al-Si in the can and bring it to the bath temperature is usually too long and non-seat core rejects result.

After preheating, the can-sleeve assembly is submerged about two inches under the bath surface filling the can with molten Al-Si. During submersion the can is wet with Al-Si and the core and cap are assembled in the can. During the submersion time the can-sleeve assembly is vibrated to reduce braze porosity.

The preheat and submerge times are closely controlled to assure that (1) the can reaches the bath temperature, (2) the can will be wet by the Al-Si, and (3) an excessive amount of can wall is not eroded or dissolved away. There are a large number of possible combinations of can-sleeve preheat and submerge times that would work.

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b. Cap Preheat

The solid fuel element cap is preheated by submersion in the bath. During preheat the cap is aided in being wet by the Al-Si either by: (1) being vibrated or (2) being removed from the bath, abraded on a Transite board, and re-immersed in the bath. The maximum preheat time is not as important as with I & E cap-spires but wide braze lines can result if preheated too long.

The I & E cap-spire is preheated by immersing all but about two inches of the cap chimney in the bath. During preheating the cap-spire is vibrated to remove gas bubbles under the cap and to aid Al-Si wetting.

If the cap-spire is preheated less, frozen Al-Si may still be present on the cap-spire preventing proper cap seating. A preheat longer will decrease the average spire wall thickness making it easier to have a penetration reject A long preheat also makes it easier to wrinkle the spire wall during assembly.

4. Vibration

In early 1956, a can-sleeve vibration technique was developed for improving fuel element quality.[51, 52] Voids in the Al-Si bonding layer, especially those near the fuel element base, have caused a high bond test reject rate (greater than six per cent). Air trapped in the can when it is filled with Al-Si is the cause for most of the

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voids at the fuel element base. Vibration practically eliminated these base end voids and reduced the bond reject rate from greater than six per cent to less than two per cent.

This can-sleeve vibration technique operates as follows:

a. The can-sleeve assembly is clamped in the basket after complete submersion by an air-cylinder actuated wedge (See Figure 34) to provide effective vibration transmission.

b. The vibrator (A Peterson "Vibrolator") attached to the basket (See Figure 34) is then turned on after the can-sleeve assembly is completely submerged.

This vibration is produced by a steel ball being pneumatically driven around a stationary race.

c. The vibrator is turned off and the clamp released one second before the canning jack rises to the unload position.

In mid 1957, a method for improving cap wetting of the cap-spires by vibration was developed.[31] This method uses a submerged vibrating well which sets up vibrations in the molten Al-Si inside the well (See Figure 32). This vibrating Al-Si aids in removing gas pockets under the cap and aids in wetting the cap-spire. The cap-spire is either held by hand in the preheat position in the vibrating well or is held by a stationary tong holder.

The same vibrational frequency and type of vibrator is used as for can-sleeve vibration.

The vibrator is used presently during the cap-spire preheat period. The same vibration cycle can also be used for solid caps.

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5. Assembly Method

a. Solid Fuel Elements

When the solid cores are carried from the duplex to the canning bath, they are dip-washed in the molten Al-Si to remove oxide from the surface before assembling the cores in the submerged can-sleeve assembly. Two methods of inserting the core in the can-sleeve assembly have been used: (1) The method used until early 1958 was to start the core in the can and then push the core down with the tong base until fully seated. (2) In early 1958, the assembly method was changed to the slow insertion method where the core is inserted one to two inches in the can, released and allowed to seat in the can by its own weight.[53]

By the use of this slow insertion method, about 0.004 inch more of residual aluminum can was left after assembling than by the previous method. This gives an average of 0.035 inch of aluminum can wall after canning (from the original 0.045 inch) without affecting the other quality factors of the completed fuel element.

The use of the slow insertion method required a change in the can-sleeve preheat and total submerge time to allow more time for core seating.

After the core has seated, the cap is inserted in the can and seated against the core. The canned assembly is then removed from the bath and carried to the quench tank.

b. I & E Fuel Elements

When the I & E cores are carried from the duplex to the canning bath, they are dip-washed in the molten Al-Si to remove

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oxide from the surface before assembling the cores in the submerged can-sleeve assembly. Three different methods have been used for assembling the cores and cap-spires in the can-sleeve assembly. Each of these three methods used a different type of core carrying tong (See Figure 35); core-prong, splash, or spire-core tong.[31] In refering to these methods, the type of tong used is usually named; such as core-prong, splash, or spire-core assembly method.

(1) Core-Prong Method

This method was used in development of the I & E process until mid 1957. The core prong on the carrying tongs was inserted in the core bore when the core was removed from the duplex basket. After dip-washing the core in the canning bath Al-Si, the core was seated in the can by pushing on the tongs. The core prong prevented Al-Si from freely flowing out of the bore and required most of the Al-Si to flow out through the core O.D.-to-can annulus. This large amount of Al-Si flow past the can wall reduced braze porosity but decreased residual can wall thickness.

After seating the core, the tong was removed and the cap-spire was inserted in the core. Since the core bore was below the bath surface, it was necessary to "feel" for the bore with the spire tip. The aluminum spire at the canning temperature is very soft and a large amount of spire damage (wrinkles, cocked caps, and spire leaks) resulted from this method.

(2) Splash-Tong Method

This method was used briefly in mid 1957. With the splash tong the core was inserted about one to two inches in the can and released, allowing the core to seat by its own weight. The splash shield deflected Al-Si spurting from the

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core bore away from the operators. The cap-spire was then inserted the same as in the core prong method.

The splash tong method increased the residual can wall thickness but increased braze porosity giving bond reject rates greater than 25 per cent.

(3) Spire-Core Method

This method has been used exclusively since mid July, 1957, for canning I & E fuel elements. The use of this method is one of the main reasons that over-all canning yields were increased from less than 30 to greater than 60 per cent in July and August, 1957.[31]

The spire-core method as shown in Figure 33 consists of (1) inserting the core part way into the can-sleeve assembly, (2) inserting the cap-spire into the core until seated against the core, and (3) seating the cap-spire and core simultaneously in the can-sleeve assembly.

This method improved canning by (1) reducing the spire wrinkling and damage since the core bore can be observed and there is no need to "feel" below the bath surface hunting for the bore, (2) reducing the can wall erosion by allowing part of the Al-Si in the can to flow out of the core bore before inserting the cap-spire, and (3) reducing the assembly time which will reduce penetration rejects.

After assembling the I & E fuel elements, they are removed from the canning bath and carried to the quench tank.

6. Bath Life and Impurities

The period of bath use is determined by the concentration of soluble impurities that are detrimental to the canning process or appear as quality defects in the canned element. In the early period

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of the lead dip process, limits were established for lead and uranium concentration in the Al-Si canning bath. Continual relaxation of these limits up to the apparent solubility point of the impurities revealed no detectable ill effects. Under current operating conditions, the Al-Si bath is not replaced unless an unusual contamination problem arises.

A sample of the Al-Si bath is taken each week for analysis of bath impurities by the Analytical Laboratory. The bath impurities build up rapidly to their saturation value with fluctuations due to dragout and makeup additions. The average saturation values of the major impurities found in the Al-Si canning bath are:

Iron	1.0 per cent
Lead	0.2 per cent
Uranium	0.1 per cent
Chromium	0.05 per cent
Nickel*	0.03 per cent
Titanium	0.02 per cent

*1245 aluminum alloy only. When using M-388 components or scrap, the nickel limit is controlled to less than 0.5 per cent.

In 1954 and early 1955, the lead concentration often was greater than 0.25 per cent and a peculiar defect in the weld bead of the finished fuel element was attributed to this increased lead content.[54] This defect consisted of a silicon-rich spike or pipe originating at the base of the fusion zone and extending through the fusion zone to the surface. It has since been determined that welding conditions can cause this type of defect without a high lead content. High lead concentrations (over 0.25 per cent) were eliminated by better agitation of the core in the duplex Al-Si layer and more frequent skimming of the duplex interface layer.

Impurities other than those detectable by spectrographic analysis are also important. Such contamination as fly-ash, dirt, oil, and excess oxide on equipment and metal additions to the bath are

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believed to effect Al-Si viscosity and weld quality and should be removed if possible. The reclaimed Al-Si from lathe turnings are fluxed to remove oxides, gas, and other non-metallic impurities.[55]

All of the undissolved impurities in the canning bath denser than Al-Si collect on the walls and bottoms of the furnace and the lighter impurities collect in the surface dross. This buildup of heavy material also occurs in the induction channels of the furnace requiring the channels to be broached. This broaching operation is done each day, including weekends, to prevent restriction of metal flow.[47] The buildup on the furnace bottom and walls is removed by scraping down the walls and cleaning the bottom each weekend.

The surface area of the canning bath where the cores are dip-washed and inserted into the can-sleeve assemblies is skimmed every cycle during the can-sleeve submerge period. This skimming prevents entrainment of dross in the finished assembly.

C. Fuel Element Quench

A cold water quench following the canning bath assembly completes the dip brazing operation. The fuel element is quenched as soon after assembly as possible to stop the dissolution of the can and spire walls. Quenching also facilitates removal of the the fuel element from the sleeve and lowers the temperature so they can be handled with gloves.

1. Solid Fuel Elements

Until 1955 all of the fuel elements were quenched manually in a simple basket that was lowered into the cold flowing quench water. The pieces were quenched in two stages; the first stage was to immerse all but about one inch of the sleeve top until the Al-Si on top had solidified and the second stage was to submerge the assembly.

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In 1955 an automatic quench machine was installed that operated as follows:

a. The sleeve assembly was brought from the canning bath and dropped in a holder.

b. An air operated plunger seated the caps firmly against the core.

c. A water spray cooled the sleeve until the Al-Si on the cap was solidified.

d. The assembly was submerged in water until cool.

c. The machine unloaded the sleeve assembly at an unload station.

2. I & E Fuel Elements

When quenching I & E fuel elements, the cap-spire must be re-seated against the core since the well type caps usually float. Therefore, the I & E manual quench baskets were made with cap hold-downs as shown in Figure 36.

After re-seating the caps, the sleeve assemblies are immersed until about one inch of the sleeve remains above the water surface. When the Al-Si in the cap well has solidified, the assembly is immersed further in the water, but not far enough to get water inside the cap-spire. If water enters the spires, large numbers of base end weld rejects will occur and a lathe maintenance problem due to rusting will result.[21]

The time of quenching is adjusted to have the fuel element temperature high enough to evaporate small amounts of water, which may have splashed into the spire, before the pieces are machined.

The use of high boss caps (See Figure 14) may prevent cap floating but seating before quenching will still be required to reduce high cap rejects.

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A prototype automatic quenching machine that will handle I & E and solid fuel elements has been developed and used for ten months on one canning line and is expected to be used shortly on all lines. This machine is similar to the one now in use for solid elements, except that it submerges the assemblies before the Al-Si has solidified and has no spray cooling unit. No apparent ill effects on I & E pieces have resulted from submerging the molten Al-Si to date. It was thought in the past that this practice would produce large braze layer voids between the cap and can due to steam formation in the Al-Si. Methods of delaying the submersion of the Al-Si in the cap reservoir until the Al-Si has frozen are being investigated, however.

When the quenched assemblies are removed from the quench tank, the operator removes the canned fuel elements from the sleeves. The canned elements are placed in a pallet on a hand truck and sent to the finishing area. The obvious canning assembly rejects are segregated and sent to the core recovery area. The sleeves are returned to the sleeve cleaning machine by the overhead "Zig-Zag" conveyor system.

D. Brazing Cycle

The various operations in the duplex bath, canning bath, and quench tank must be synchronized closely to produce the best possible brazed assembly. There are two canning jacks per canning furnace, two quench baskets per automatic quench tank, and the duplex basket holds four cores. This allows two pairs of fuel elements to be canned concurrently but not with simultaneous operations.

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The core carry time between the duplex and canning bath is limited to minimize core heat loss and oxidation of the Al-Si coat. The time to transfer the canned assembly from the canning bath to the quench tank is also limited to minimize further dissolution of the can and spire wall by the Al-Si.

Several different cycles have been used in the past. The difference between them is chiefly in the sleeve preheat and sleeve submerge and assembly times.

In 1955, a cam operated pneumatic actuating system was put into operation to operate the duplex bath, canning bath, and automatic quench tank equipment. The cam drive was interlocked with the clock face control system.

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The cams used on this system had a fixed cut cam to obtain the proper cycle times and/or the sequence of each operation. In order to change cycle times and/or sequences of operation, it was necessary to fabricate new cams. These changes required considerable time and money.

Therefore, a more flexible cycle-timing control system was developed in 1956 and replaced all of the cam and clock face systems in 1957. This system uses an electro-pneumatic timing instrument (a Taylor Flex-O-Timer) which actuates the pneumatic or electrical devices for the duplex agitator, canning jacks, vibration equipment and automatic quench machine.[57]

The cycle times and/or sequences of operations can be changed in a few minutes. The cycle time is changed by replacing a set of gears and the sequence of operations is changed by moving pens on a drum. Figure 39 shows the two interlocked Flex-O-Timers used for one canning line. The pins which actuate the various operations can be seen on the drums in the upper instrument. When the drums rotate, these pins actuate electrical switches which in turn operate the equipment.

E. Major Brazing Problems and Development Programs

1. Brittle Bonding[46, 58, 59]

During brazing, the bond formed between the uranium core and the Al-Si braze material is often brittle. This brittle bond can be cleaved very easily either before or during irradiation. The cleaved or broken bond impairs heat transfer from the core through the jacketing material to the process water. This may lead to localized overheating of the aluminum jacket resulting in a fuel element rupture by corrosion of the jacket. Also, these cracks reduce the effectiveness of secondary corrosion barriers produced by the compound layers.

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There is at present, no reliable nondestructive way to test for brittle bonds. Some brittle bonds that have already cracked can be detected, however, by the ultrasonic bond tester. The present method for determining brittle bonds is to chisel manually the can from the core. During chiseling, the brittle bonds are cleaved easily and the jacket is readily parted from the core. With tough bonds cracks formed by chiseling are not propagated as easily due to non-continuous cleavage planes characteristic of tough bonds.

Examples of typical brittle and tough bonding layers are shown in Figure 40. The brittle bonds are usually more uniform and thicker than the tough bonds. As shown in Figure 40, there is nothing present to stop the spread of a crack in the brittle bond but in the tough bond the cracks if formed are stopped by the non-continuous phases in the compound layer.

With tough bonds there is generally an irregular boundary between the compound layer and both the uranium and Al-Si. An irregular but fairly continuous compound layer which has sluffed away from the uranium is commonly found separated from the base compound layer by a layer of silicon-depleted Al-Si; the silicon is believed removed from the Al-Si by reacting with the compound layer.

The brittle bonding is not always uniform throughout the core surface. Brittle bonds are found primarily near the cap end of a canned assembly. In fact, many fuel elements have a tough bond over most of the core surface and a brittle bond on the cap end extending down the core for about one or two inches. In the past, this type of a broken bond usually resulted in what was called a No. 4 reject on the frost test machine. These rejects appeared as large melted areas of acenaphthene below and around the cap of the canned assembly.

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Much work has been done in the past and present to produce a tougher and more uniform bond. The bonding studies are complex due to the large number of interacting variables that can effect bonding strength, ductility, and uniformity. Some of the obvious variables are:

a. Temperature of the brazing baths.
b. Composition of the brazing baths. (Particularly the duplex bath)
c. Immersion times in the various layers and baths.
d. Uranium core surface preparation.
e. Al-Si and lead layer levels in the duplex bath.
f. Interface layer conditions in the duplex bath.
g. Duplex basket design.

Tougher bonds have been produced by increasing duplex lead and Al-Si temperatures and by reducing the silicon content of the duplex Al-Si.[46]

Bond uniformity is influenced by Al-Si and lead layer levels, basket design, and duplex bath temperature variations. During preheat in the lead layer, the closer the core is to the interface layer the greater is the number of cap end brittle bonds. Therefore, dropping the core deeper into the lead layer (giving three to six inches of lead cover) has decreased this problem. Also, increasing the Al-Si cover over and under the core to at least two inches in the Al-Si layer has helped increase bond uniformity.

The use of a nearly horizontal duplex basket produced the most uniform bonding to date.[46] This horizontal basket, however, was not suitable for production but a suitable design has been developed and is now being tested. A prototype automatic core basket loader is also being tested.

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Better control of the power input of duplex furnaces (as discussed previously in Section IV, A, 1) has resulted in less temperature variations in the baths. This in turn reduced variations in bond ductility and compound layer formation.

The average I & E fuel element has a more ductile bond than the average solid fuel element and the compound layers are different. This difference is believed due to the lighter weight and greater surface area of an I & E core.[46]

Not much work has been done in the past on measuring bond tensile strengths due to the difficulty of preparing and attaching pull-bars and the inconsistency of the results. The area being tested is mechanically separated from the remainder of the can wall by cutting a groove through the can wall and bond layer around this area. This cutting operation may reduce the true tensile strength of the sample by cracking the bond layer. Pull-bars have been attached by two methods; a high strength adhesive and stud welding.

A program has been outlined for studying the process variables to improve the bond ductility and quality.[22] Some of these programs are:

a. Identify the bond layers and establish the basic metallurgical nature of these bonds. Differentiate between a good bond and a poor bond structure and develop reliable techniques for measuring bond properties.

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b. Determine the effect of canning and preparation variables on bond structure and strength. This includes such items as bath temperature, Al-Si viscosity, silicon content in the Al-Si, core surface preparation and roughness, effects of duplex bath interface layer, layer level thickness, immersion time, basket design, and agitation method and rate.

c. Optimize the quenching operation to assure that this does not contribute to cracked bonds.

d. Evaluate the use of mechanical vibration in the baths to improve the bond.

e. Determine the bond layer resistance to cleavage upon thermal cycling.

f. Determine the resistance of good bonds to water under-cutting the bond layers.

g. Determine the effects of additives to the baths to improve bonding.

h. Investigate the mechanical property effects of jacketing alloys on bond stability.

2. Braze Layer Porosity[61, 62]

Gas porosity of varying amounts has always been a problem in Al-Si brazing of fuel elements. This porosity between the uranium core and the aluminum jacket results in non-uniform heat transfer that may cause localized corrosion and subsequent fuel element rupture during irradiation. Braze porosity between the aluminum can and cap also contributes to defective welds which can cause ruptures by water entry to the uranium core. At the present time, inspection of the assembled fuel element is done by visual weld inspection, by ultrasonic bond testing, and by radiographing the cap end braze layer in an effort to prevent fuel elements with unsuitable porosity from being used in the reactors.

From a review of the brazing operation, the following sources of gas contamination are possible:

(1) Uranium core
(2) Aluminum cap and can
(3) Entrapped air
(4) Molten Al-Si baths
(5) Contaminates on the sleeves

[redacted]

Of the above sources, the uranium core is considered to be the major source of gas porosity. Each of the above items will be discussed in detail below.

a. Uranium Core (38, 63, 64)

Early in the lead dip process (1953) it was noted that hydrogen gas was evolved from solid uranium cores during the brazing operation. Virgin uranium cores were observed to have gas bubbling through the molten Al-Si coating when removed from the duplex bath.

Starting in September 1954, uranium cores containing large amounts of hydrogen were received from Fernald and bond rejects were often greater than 30 per cent. Investigation traced the source of the hydrogen to the use of a new carbonate salt beta-heat-treating furnace at Fernald. Prior to the trouble, Fernald had heat treated in a gas-fired carbonate salt bath. Since this furnace was unable to handle production requirements, a larger immersed-electrode furnace was built and put into use in August, 1954. At this time the gross hydrogen problem started.

As a remedial measure, virgin uranium cores containing greater than about 2.5 parts per million hydrogen were out-gassed in a chloride salt bath. This outgassing procedure was used for about six months. After this time the hydrogen content of uranium received was in the range of 2.0 to 2.5 ppm except for special material such as dingot uranium. Salt bath out-gassing is done in a eutectic barium-sodium-potassium chloride salt at 600 to 620 C for five to six minutes, with vigorous agitation (over 450 RPM). After removal from the salt bath, the cores are quenched within 10 seconds in cold water.

This salt bath outgassing reduces the hydrogen content on the core surface, since the solubility in the high alpha temperature range is only one ppm while the solubility under beta heat

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treating conditions is 8 to 9 ppm. This operation does not significantly alter the metallurgical characteristics of the uranium core but the core surface is affected by the salt and a longer pickling time must be used.

Since the gross hydrogen problem arose, considerable work has been done at HAPO and offsite in trying to prevent hydrogen pickup. It was found that when the hydroxyl content of the lithium-potassium carbonate salt is about 1 1/2 per cent, the hydrogen problem will be severe; when the hydroxyl content is 0.5 to 0.75 per cent the problem is moderate. Carbon dioxide gas bubbled through the salt bath reduced the hydroxyl concentration and thus helped lower the hydrogen pickup by the uranium.

Examples of the effect of hydrogen concentration in uranium on braze layer porosity is shown in Figure 16. Stripping can jackets with their accompanying autoradiograph films are shown at hydrogen concentrations of 0.5, 2.2 and 4.0 ppm. Vacuum outgassing at about 600 C is effective, as shown, in removing hydrogen from uranium, but it is not feasible for production operation. The dingot uranium shown is included to show the effect of high hydrogen concentration.

Other heat treating mediums have been used besides a lithium-potassium carbonate salt. Molten metals such as bronze and lead are effective and the chloride salt used for salt bath outgassing is known to be better than the present method. Both chloride salts and molten metals present severe problems to Fernald but a program is now under way to heat treat uranium in core blank form in a chloride salt bath.

A large number of studies have been made at HAPO in trying to reduce the severity of the hydrogen-from-uranium problem.

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Results on some of these studies are as follows:

(1) Immersion time in the duplex bath

Braze porosity increased as the time of core immersion in either the lead or Al-Si layer was increased.[38]

(2) Core surface oxidation[38]

Braze porosity increased with increased amounts of uranium surface oxidation.

(3) Recovered cores

Braze porosity is less in recovered cores than in virgin metal of similar history.

(4) Bath Life[38]

There is no apparent relationship between porosity and length of bath life.

(5) Core Pickle[38]

Normal contact with trichloroethylene, nitric acid, and water during core preparation has no significant effect on porosity.

(6) Agitation in the canning bath[38]

Porosity is reduced by agitating the core in the canning bath just prior to core insertion. However, this practice is believed conducive to brittle bonds.

(7) Duplex basket design [64]

Duplex baskets with a minimum amount of shielding effect had less porosity than "closed" baskets. "Closed" baskets prevented accumulated gas on the core surface from being washed off.

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(8) Duplex agitation[64]

Porosity is reduced by increasing the speed of core agitation in the duplex bath.

(9) Time from assembly to quench[64]

Porosity is reduced by shortening the time from core insertion in the can to quenching the assembly.

b. Aluminum Cap and Can[61]

Tests have shown a negligible amount of hydrogen in aluminum caps and cans. Therefore, the aluminum components can be dismissed as a source of gas porosity.

c. Entrapped Air[52, 61, 66]

The majority of the large braze voids near the base of the core were found to be caused by entrapped air. The air was found by extracting the gas from the void by drilling though the can wall in vacuum equipment attached to a mass spectometer. Analysis of the gas showed a high percentage of nitrogen and argon.

The use of pneumatic vibrators on the canning jacks has reduced this condition by shaking the bubbles free from the can wall before core insertion and probably disperses them during and after core insertion. From September 1956 to February 1957, the bond test reject rate was reduced from an average of 10.1 to 2.0 per cent.[67] During this time, vibration equipment was being gradually added to the canning baths.

d. Molten Al-Si Baths

Hydrogen dissolved in molten Al-Si can be a source of gas porosity since the change in solubility upon solidification is a factor of about 19 to 1. The hydrogen can be introduced into the Al-Si from air moisture, scrap, and dirty tools.

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Hydrogen removal has been tried by sparging the bath with nitrogen and carbon dioxide gas with no apparent improvement. However, no accurate method was available at the time to measure hydrogen in the bath. A hydrogen gas meter capable of detecting hydrogen in molten Al-Si has since been obtained and more tests are planned using inert gas sparging.

e. Contaminates on the Sleeves

Prior to August 1958, soap was used to coat the sleeves. The soap decomposed in the canning bath forming gaseous compounds that could cause braze porosity if carried into the assembly. The non-hydrogenous coating now used, sodium aluminate, forms no noticeable gaseous compounds in the canning bath.

f. Porosity Reduction Program

A program has been outlined to reduce hydrogen evolution from the core and air entrappment during brazing. Some of these specific programs are:[22]

(1) Chloride Salt Bath

Reduce surface hydrogen in uranium cores by converting to chloride salt-bath heat-treatment at Fernald. If this is insufficient, find improved heat treating processes that will be effective in giving a low hydrogen content.

(2) Vibration

Continue optimizing vibration for eliminating entrapped gas from the can-sleeve assembly during the brazing operation.

(3) Gas in Molten Al-Si

Determine the contribution of dissolved gasses in the molten Al-Si to braze porosity and find ways to eliminate or reduce the problem.

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(4) Removal of Extrapped Gas by Mechanical Methods

Devise and evaluate mechanical means other than vibration to remove entrapped gas from the can sleeve assembly.

(5) Additives to Bath

Determine the value of "getters" or additives in combining with dissolved gasses and in reducing surface dross to reduce braze porosity and impurities.

3. Spire Damage[31]

Spire damage during preheating and cap assembly was a common type of reject during the early work on I & E fuel elements. Spire damage usually resulted in one of the following:

a. Spire leaks where the spire is damaged or erroded enough to allow molten Al-Si to enter the spire bore.

b. Penetration rejects where less than 0.020 inch of residual aluminum wall remain after quenching.

c. Wrinkles and bumps which are large enough to result in a mandrel reject or which will cause a false "penetration" reject. During the finishing and inspection of the canned assemblies, the I & E pieces are tested with a mandrel 0.015 inch smaller than the nominal spire I.D. to assure an adequate passage for water during irradiation. Due to the geometry of the I & E element, the internal penetration tester is incapable of distinguishing between an Al-Si penetration, a spire wrinkle, or a void in the braze layer. This makes the internal penetration reject rate much higher than the true value.

d. Cocked caps if the spire is bent during spire insertion.

Several techniques and developments have been made which helped reduce spire damage. They are:

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a. Use of the spire-core canning technique. The use of this method (see Figure 33) gave the greatest reduction in spire damage of any change in canning technique. This method reduced spire wrinkling and damage since the core bore could be easily seen and there was no need to "feel" below the bath surface hunting for the bore.

b. The use of tapered can recesses (Figure 13) which prevented the spire from gouging into the step in the can recess and wrinkling the spire.

c. Better spire closure techniques were developed giving a thicker spire tip and therefore less spire leaks.

Some spire wrinkling still occurs and is believed due partly to bottom freeze-out preventing the spire from being seated properly in the can base recess. Bottom freeze-out occurs when the can base is not preheated sufficiently to remelt the Al-Si that freezes in the base of the can when the can-sleeve assembly is submerged. This frozen or partially frozen Al-Si in the can base recess exerts back pressure on the spire during insertion and wrinkles the spire wall. A program to reduce the bottom freeze-out problem includes:

a. A longer can-sleeve preheat. This could be supplied by a longer brazing cycle, supplemental preheat in a muffle furnace or induction coil, or by using the single jack canning method (Section IV, E, 11).

b. The use of contoured can bases. Up to forty per cent of the can base metal could be removed from the can base without damaging the finished fuel element. This would decrease the amount of heat needed to preheat the can base and would decrease the preheat time necessary to reach the melting temperature of Al-Si.

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c. The use of bottomless sleeves. Without a bottom in the steel sleeve the heat transfer rate to the can base will be increased. This increase may be sufficient to prevent the bottom freeze-out problem.

4. Cap-Spire Floating

The I & E well type cap-spires float after spire insertion and must be re-seated before quenching to prevent high cap rejects. The manual I & E quench baskets are made with cap hold-downs as shown in Figure 36. This method is usually satisfactory but occasionally a cocked cap results when the hold down does not contact the cap properly.

A new cap-spire design, the high boss cap, (Figure 14) does not float as much and will reduce cocked cap rejects. Large scale use of this new cap is not expected until early 1959.

Several designs of internal steel weights to reduce cap floating have been tried. They have proven to be unsuitable for production work. When using steel weights, a longer cap preheat is necessary, the residual spire wall is reduced, and more spire damage results. Also, removal of the weights either before or during machining is difficult and slow.

5. Aluminum Non-Wetting

Aluminum non-wetting is the lack of a bond between the aluminum components and the Al-Si braze material. Non-wetting is associated with (1) the cleanliness and amount of oxide on the aluminum components before canning, (2) the canning temperature, composition, time, and component vibration, and (3) the component material.

Recently there has been a problem in cap-spire non-wetting. This non-wetting of the I & E cap wafer has reduced weld closure integrity and contributed to several autoclave and reactor failures, particularly in the seven-inch depleted I & E fuel elements.[41]

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As an immediate solution to the problem, a process was developed for etching the cap wafer in a five per cent caustic solution (Aluminux) prior to normal cleaning (Section III, F, 1). This effectively removed the heavy oxide film and has essentially eliminated the cap wafer non-wetting problem. A spire etching line is being installed and will be put into service the first part of December, 1958, for etching all I & E cap wafers.

The non-wet problem is more serious with M-388 alloy components than with 1245 alloy. The M-388 alloy components are not only received with a heavier layer of extruding lubricant but they are also harder to wet with molten Al-Si than the 1245 alloy. After the M-388 alloy is wet, however, the aluminum appears to dissolve faster in the Al-Si than does the 1245 alloy.

The cleaning procedure for aluminum components (Section III, A) in the automatic cleaning machines is not the best possible method. However, to convert the existing machines to the better method (an immersion degrease) would require extensive and expensive equipment modifications. New and better cleaning methods suitable for existing and new equipment are under development. This includes ultrasonic cleaning equipment.

Other major development programs for reducing the aluminum component non-wetting problem includes:

a. Adjustment of canning bath variables. The adjustment of canning bath variables to assure wetting will be studied in conjunction with the brittle bond problem (Sec. IV, E, 1). These variables include bath temperature, Al-Si viscosity, silicon concentration, immersion time, and vibration method and rate.

b. Al-Si clad components. Development quantities of Al-Si clad cap-spires have been used which assured complete wetting of the cap and spire. These cap-spires are extruded from blanks

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with a layer of Al-Si alloy bonded to the standard aluminum alloy. The resultant finished cap-spire has an Al-Si layer from 0.005 to 0.010 inch thick on the outside surface of the cap wafer and spire. When the cap-spire is preheated, the Al-Si melts and the base aluminum alloy is completely wet.

The major drawback to these clad cap-spires is the high cost. Presently they are 45 cents a piece higher than the regular cap-spires, but with large orders this should be reduced to about 25 cents. About 10,000 clad cap-spires are now on order for test purposes. Solid caps have also been made with Al-Si cladding with good wetting results but high cost.

The aluminum component vendors are also attempting to develop I & E and solid cans that are Al-Si clad on the inside.

c. Mechanical methods. Several mechanical methods of aiding component wetting and removing the bubbles that are commonly formed under the cap wafer are being investigated. This includes (1) swirling the cap-spire in the bath, (2) abrading the cap wafer under the bath surface, and (3) forcing molten Al-Si past the cap wafer with a small pump.

d. Fluxing. Several methods of using aluminum fluxes to aid in wetting cap-spires are being investigated.

e. Immersion plates. Immersion plating processes, such as the zincate process, are being tested for improving wetting on cap-spires. The immersion plates will only adhere to the aluminum where the oxide layer has been removed. Thus, if a good immersion plate has been applied, it will be only on cap-spires with the aluminum oxide layer removed. The immersion plates will also prevent the reforming of aluminum oxide. If a plate of a low melting metal, such as zinc, is used, the plate should melt off quickly in the Al-Si bath producing a continuously wet cap-spire.

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f. Thick wall components. If thick wall components are used the components could be etched more during cleaning or allowed to dissolve more in the canning bath which should aid in component wetting. At the present time 10,000 thick wall (0.050 inch) cap-spire are on order and are expected to arrive in February 1959. No thick wall cans have been ordered to date.

6. Residual Aluminum Wall Thickness

The amount of residual aluminum jacket thickness must be great enough to give corrosion protection to the fuel element while it is in the reactors. The corrosion rate depends on the aluminum surface temperature and the time in the reactors. These two values vary greatly depending upon reactor conditions, fuel element design, and type of uranium core. Considering the reactor corrosion loss and amount of mechanical surface damage during reactor loading, it is estimated that 0.020 inch of residual aluminum can and spire wall are adequate protection for present reactor conditions.

Therefore, all fuel elements are tested by an electromagnetic penetration device to assure that 0.020 inch of residual aluminum can and spire wall remains. However, to prevent an excessive number of penetration rejects, the average residual aluminum wall thickness must be greater than 0.030 inch.

Canning conditions, cycles, and assembly methods have been developed to give the greatest possible average residual wall thickness to date. For example, when the solid canning cycle was changed to the slow insertion method[53] the amount of can wall eroded away was reduced from an average of 0.014 to 0.010 inch.

With the adoption of the cap-spire canning technique (Figure 33)[31] the amount of can wall eroded away was reduced making it possible

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to reduce the as-received can wall thickness from 0.045 to 0.040 and 0.038 inch. The present amount of can and spire wall erosion averages 0.008 and 0.010 inch respectively.

There must, however, be enough can wall erosion to assure complete wetting of the aluminum jacket. Therefore, any new canning techniques devised must be a compromise between aluminum wetting and maximum residual aluminum wall thickness.

If a ductile continuous uranium-Al-Si bond and a nonporous Al-Si braze layer can be developed, it may be possible to reduce the aluminum wall thickness requirement and rely on total aluminum plus Al-Si thickness for corrosion protection.

7. Braze Contamination

During the welding of fuel elements, inclusions in the weld bead are a common type of reject (often greater than five per cent for I & E fuel elements). The chief source of these inclusions is braze layer contamination. The contamination is either intermetallic compounds, such as bonding layer particles, or non-metallic materials, such as aluminum oxide and dross.

These particles are usually too small to disrupt proper heat transfer from the uranium to the reactor water. But, they can reduce the secondary corrosion protection provided by the Al-Si in case of water entry through the aluminum jacket.

The best method to reduce braze contamination is to have good process cleanliness. Frequent skimming of the dross on the bath surfaces and the interface layer helps prevent contamination from these sources. Clean tools, equipment, and metal additions used in the baths are also important.

The Al-Si metal additions made from reclaiming aluminum scrap are given a fluxing treatment during the scrap melting operation to remove non-metallic impurities. The source of the scrap

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is from facing lathe turnings and reject aluminum cans and caps.

The flux used until June 1958, was Soffelite No. 2, a chloride flux. At that time a cover flux and a degassing flux was adopted for treating the scrap Al-Si. The cover flux is Coverall 11, mainly chlorides and carbonates, and the degassing flux is Degasser 300, mainly hexachloroethane. The cover flux is added to the Al-Si surface and the degassing flux is plunged to the bottom of the furnace and agitated by hand to get good mixing. After fluxing, the melt is skimmed frequently to remove flux and dross. Three hours after fluxing the melt can be bailed into clean dry molds.

8. Faster Cycles

Another possible cycle being studied is one that combines the duplex and canning bath in one furnace to achieve a more efficient operation. This change might require induction preheating of the can-sleeve assembly and core since it is doubtful that the present furnace could carry the heat load.

9. Alloy Additions to the Al-Si Baths

Small amounts of certain elements (Na, Be, Ti, Ca, Zr, Ce) are sometimes used in foundries to give better castings. Their usual effect is to reduce dissolved hydrogen in the melt, increase fluidity, and decrease the freezing temperature.

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One of these elements, beryllium, has been studied by HLO as a possible addition to the canning bath Al-Si.[68] It is reported that beryllium reduces dross formation, increases fluidity, and reduces surface tension. However, there is a toxicity problem in using beryllium alloys.

Further development work on alloy additions are to be made under the brittle bond and porosity programs.

10. Can-Spire Component Canning[23]

A one piece can-spire component with a simple cap (See Figure 15) has been developed and demonstrated to be feasible on a small scale. The use of these components would eliminate one facing and one dimensional inspection operation. A set of components, cap and can-spire, are also about 18 to 20 cents less than for the present can and cap-spire.

Higher yields are expected through reduction of the number of assembly, facing, spire wrinkle, and marred surface rejects. Equipment modifications are needed in welding to make two welds on one end and in can cleaning to drain the can-spire assemblies both ways.

About five thousand can-spire components are on order to determine the feasibility of using these components.

11. Single Jack Canning

A canning method using only one canning jack is under development. This method should produce better fuel element uniformity since the can-sleeve basket is located near the bath center where the temperature is more uniform than near the furnace walls.

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Also a longer can-sleeve preheat time is possible with this method which should help decrease spire wrinkling by eliminating the bottom freeze-out problem (Section IV, E, 3). The can-sleeve assemblies are preheated in a stationary holder in the bath and transferred to the can-sleeve basket just prior to submersion.

A four man canning crew is still used but with different work assignments than used previously. The present work assignments are: (1) a carrier inserts cold cores in the duplex basket, transfers cores to the canning bath, inserts cores into the can-sleeve assembly and carries assembled fuel-element-sleeve assemblies to the quench tank, (2) two cappers insert cold can-sleeve assemblies into the canning baskets, preheats cap-spires, and inserts cap-spires during assembly, and (3) a quench tank operator. With the single jack canning method the work assignments are: (1) a duplex carrier inserts cold cores into the duplex basket, transfers cores to the canning bath, and inserts cores into the can-sleeve assembly, (2) a capper inserts cold can-sleeves into the preheat holder, preheats cap-spires, and inserts cap-spires during assembly, (3) a canning carrier transfers preheated can-sleeve assemblies from the preheat holder to the canning basket and carries assembled fuel-element-sleeve assemblies to the quench tank, and (4) a quench tank operator.

V. Fuel Element Finishing and Inspection

During the fuel element finishing and inspection operations, the fuel element assembly fabrication is completed and inspected to assure that only good quality fuel elements are sent to the reactors for charging. The sequence of finishing and inspection operations for I & E fuel elements is shown in Figure 1 following water quench.

This particular sequence for I & E fuel elements has only been used since February 1958. Prior to that time the I & E elements were cap end faced, cap end welded, base end faced and base end welded instead of the present face-face-weld-weld operation.

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The solid fuel elements are finished and assembled in a manner similar to I & E pieces except that fuel element stamping is done after quenching and prior to welding.

In 1956, the cap radiograph was moved from after fuel element etch to after final inspection. This permitted a better flow of material with less hold-up time and improved manpower efficiency.

The weld recovery operation was added in March, 1958. This operation reclaims between 72 and 79 per cent of the weld inspection rejects. Also in February 1958, the reclamation of inclusion rejects was started on a routine basis by re-etching and re-autoclaving these rejects. Both re-welding and re-etching are permitted only once. The reclamation of long length rejects and re-etching of stained fuel elements has been done for several years.

A. Fuel Element Machining

The cap end of all canned assemblies and the base end of I & E assemblies are machined (faced) to remove the excess metal to produce a fuel element of the right length and with the correct end contour. The facing is done in such a manner that the Al-Si braze layer is clearly visible for inspection. Also, the cut must be smooth and clean to facilitate welding. A surface finish of 125 microinches (RMS) is usually satisfactory.

The present machining lathes are six spindle automatic Acme-Gridley lathes. (See Figure 41) The operations performed by these lathes in facing I & E fuel elements are:

1. Cap End Face

a. Load and Index. The lathe operator places the piece in a loading chute and the piece is pushed into the collet by an indexing shaft pushing on the top of the cap wafer on a well type can or on the top of the boss on a boss type cap. This indexing shaft

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pushes the piece into position so that only the required amount of cap will be removed in machining. For the well type cap 0.040 inch ± 0.005 inch is faced off the aluminum cap wafer.

b. Rough Cut. The chimney and excess Al-Si braze material is cut off using a carbide tip or a Rex AAA tool.

c. Contour Cut. The forming tool faces the pieces to the required shape and depth with a Rex AAA tool.

d. Chamfer O.D. The O.D. is chamfered to remove the rough flared edge left on the piece after contouring. If this rough edge is not removed, weld rejects such as oxide inclusion are likely to result. The chamfering knife is positioned about 74° to the faced surface of the cap and is set to remove less than 0.050 inch of can wall measured along the fuel element axis.

e. Bevel I.D. The I.D. is beveled to remove the rough flared edge left on the tube after contouring. If this rough edge is not removed, it may damage the internal probe used for internal bond and penetration testing. The maximum bevel used is 0.080 inch plus the tube I.D. provided that the beveling tool used does not have an included angle less than 80°.

f. Unload. The finished fuel element is automatically ejected onto an unloading chute. It is then removed by the operator and placed on a pallet truck or on a conveyor. The process then passes through a length and braze inspection station before going to the base end facing operation.

2. Base End Face

a. Load and Index. The lathe operator places the fuel element in a loading chute and the piece is pushed into the collet by an indexing shaft pushing on the can base. This indexing shaft pushes the piece into position so that only the required amount of base will be removed in machining. For I & E fuel elements this amount is 0.535 inch ± 0.010 inch.

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b. Rough Cut. Most of the can base metal is removed by a Rex AAA roughing tool.

c. Contour Cuts. Two lathe positions are used for machining the contour to the required shape with carbide tip tools.

d. Chamfer O.D. The O.D. is chamfered similar to the cap end O.D. to remove the rough flared edge left after contouring. If this rough edge is not removed, a rough sharp oxide is formed when the weld arc is started which can damage the external penetration equipment when the piece is tested.

e. Unload. The finished fuel element is automatically ejected onto an unloading chute. It is then removed by the operator, stamped, and placed in a conveyor which passes through the length and braze inspection station to the welders.

Before the use of the six spindle automatic Acme-Gridley lathes in early 1955, the machining was done on single spindle Lodge and Shipley engine lathes.(70) Prior to facing on the engine lathes, the fuel elements were sent through a marking fluoroscope. With this fluoroscope the operator positioned the top of the uranium core at a reference point and a knife inscribed a mark on the can wall at a set distance above the core. The piece was then machined by hand feeding down to this inscribed mark and deburred with a file.

After machining in the engine lathe, the fuel elements were examined by an inspection fluoroscope to determine if the piece had the proper cap thickness. Also, the base end was examined by the fluoroscope to detect any high non-seat rejects.

There was one major weakness in this type of facing operation. That is, that it was impossible to tell how much aluminum cap thickness remained on the faced fuel element since Al-Si and

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aluminum have about the same density. If a piece with a high cap or a cocked cap is faced, it is possible to have Al-Si braze material extending from the core to the faced cap surface.

With the indexing method now used on the Acme Gridley lathes, the aluminum thickness is assured of being adequate and the total fuel element length will vary according to the Al-Si braze thickness on the top and bottom of the core. The use of mechanical cap hold-down devices during quench assures the uniformity of the braze thickness. The minimum acceptable residual aluminum cap and base thickness on I & E fuel elements is 0.250 inch.

B. Faced Fuel Element Inspection

Fuel elements are inspected statistically after facing to assure an acceptable quality piece. The maximum braze line width is controlled to assure sufficient silicon dilution for a sound corrosion resistant weld and adequate weld bead cover over the braze line. A wide braze line also indicates some abnormality in the brazing operation that may need correcting.

The fuel element length and end contours are also controlled to provide optimum aluminum coverage and proper mating of the fuel elements in the reactors.

After the adoption of the Acme-Gridley lathes in 1955, the fuel elements were inspected 100 per cent for length and braze width. In early 1956, however, a statistical sampling plan was put into practice for assuring length, cap thickness and braze width control.[71]

A six piece sample which has been faced consecutively is selected from each hand truck (60 pieces) or each 100 pieces on a conveyor for inspection purposes. The six sample pieces must be faced consecutively to be sure that one element is taken from each of the six spindles on the Acme-Gridley lathe.

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The six piece sample is then inspected for: (1) surface finish and contour dimensions, (2) fuel element length and (3) braze width. The length limits for I & E fuel elements after cap end and base end facing are 9.460 inch to 9.630 inch and 8.885 inch to 9.085 inch, respectively. However, the length limit is usually controlled to 9.510 inch ± 0.020 inch after cap end facing and 8.965 inch ± 0.020 inch after base end facing. The maximum braze width permitted is 0.040 inch.

From the results of this inspection, steps are taken to correct faulty machining and brazing operations. Length rejects that are obviously machined too long are grouped into special lots and refaced on hand operated lathes. However, only 0.030 inch is allowed to be removed during the refacing operation. All other rejects are sent to core recovery.

C. Fuel Element Identification

All fuel elements have a stamped identification placed on the can base from which the fabrication history of the core, jacketing components, and canned assembly can be determined by reference to production records. Proper evaluation of materials and fabrication methods before and after irradiation depend upon these identifying marks.

Uranium cores of similar geometry, fabrication history, and feed material make-up are grouped into separate lots. A lot is then canned in a consecutive operation so that the canned fuel elements will have a common fabrication history insofar as practicable.

There have been a number of different identification schemes used in the past several years. The present scheme (shown in Figure 4) consists of six and sometimes seven characters which are stamped on the can base.[72] These characters identify the following:

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1. First character: A letter for uranium core vendor and fabrication method.
2. Second character: A letter for uranium core size, enrichment and geometry.
3. Third, fourth, and fifth characters: Numbers assigned to core lots.
4. Sixth character: A letter for aluminum jacket vendor, alloy, and geometry.
5. Seventh character: A number for the individual canning line in the 313 Building or a letter X, Y, or Z for material canned in the pilot plant. The number of the canning line is usually not stamped on the fuel element.

The stamping operation is performed on I & E fuel elements after can base machining and on solid fuel elements just prior to cap facing. The stamps are held in the base of a tubular holder and the fuel elements are inserted and slammed down on the stamps by hand.

The maximum depth of the stamping marks is limited to 0.035 inch to insure that the minimum residual can base thickness is adequate for reactor use.

D. Fuel Element Welding

The closure zones of faced fuel elements are welded to join the cap to the can wall and the can base of an I & E fuel element to the spire wall. The welding operation produces a closure zone inherently more sound than the Al-Si braze layer and reduces the silicon concentration at the jacket surface by mixing the braze layer with the cap and can alloy. Welding also serves as a test of the closure zone since porosity, impurities, and unbonded areas in the weld area generally result in weld defects that can be detected by a visual inspection.

An inert-gas-shielded A.C. arc welding method without filler metal addition is used for welding brazed fuel elements at HAPO.

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A good quality weld can be made using a gas shield of pure argon or a mixture of five parts argon to seven parts helium depending on the other welding conditions such as amperage, welding speed, gas flow, type of torch and electrode, electrode extension, and type of transformer.[73]

Prior to 1954, fuel elements were welded on manually operated welders. The fuel elements were held vertically in a motor driven spindle and the torch position was controlled manually throughout the welding cycle. In 1954, semi-automatic welding machines were installed that performed all of the crucial welding motions mechanically and electrically, leaving the operator only to load and unload fuel elements and to push the start button.[74] (See Figure 42) The operator sets the electrode extension, electrode position with respect to the brazed joint, welding current, and shielding gas flow on the semi-automatic welder. He also brushes the weld area with a motor driven wire buffing apparatus just prior to loading the piece in the welder. This buffing cleans the surface and makes it easier to start the arc.

By late 1957, a prototype automatic horizontal load-unload welder was developed.[75] Production models (See Figure 43) are expected to be installed and in operation in January, 1959. Fuel elements on conveyors pass through an automatic buffer to the welding machine where they are automatically loaded, welded, and unloaded onto another conveyor. The operator has only to set the current, shielding gas flow, and electrode extension.

Prior to the introduction of the I & E fuel elements, the solid fuel elements were welded using one preheat pass about 7/16 inch in from O.D. and one weld pass over the braze line. With the use of I & E fuel elements which have a tru-line contour it was necessary to develop another welding technique. This technique, which was used on both solid and I & E pieces, was a two weld pass - no preheat

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pass method. With this method the arc is struck about 7/16 inch in from the cap end O.D. and 3/16 inch from the base end O.D. but is left there only long enough to stabilize the arc before moving over the braze layer and making two weld passes.

In late 1957, another faster and simpler welding technique was developed. This was a single pass weld cycle with arc starting similar to the two weld pass method. The single pass weld cycle uses an argon-helium gas shield rather than pure argon and has a higher welding current than was used in the two pass cycle.

Before leaving the finished weld bead, the arc is uniformly decayed by lowering the current to such a degree that no further melting of metal takes place. The arc is then extinguished off the weld bead.

Up until early 1955, all of the welds were quenched by submersion of the weld area in cold water. This reduced the temperature for ease in handling at weld inspection and for uniformity of frost test coating. With the use of the conveyor system there was enough hold-up time between welding and inspection to lower the fuel element temperature to a satisfactory point and the water quench after welding was discontinued.

The fuel element welds produced must appear smooth and sound, have a weld bead width between 1/8 inch and 7/32 inch, and a minimum penetration of 0.050 inch. Weld penetration is measured from the top of the cap to the base of fusion zone on the can O.D. and from the bottom of the can to the base of the fusion zone on the spire I.D. on base end welds. The measurements are all made parallel to the fuel element axis.

The weld bead must not have too great an overhang or it will restrict the flow of reactor cooling water during irradiation. The

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maximum weld overhang is checked as follows:

1. Cap end welds must pass a ring gage not more than 0.010 inch larger than the maximum can O.D.
2. I & E base end welds must pass a mandrel gage not more than 0.012 inch smaller than the minimum spire I.D.

There are a number of different types of weld rejects that can occur from brazing defects, contaminated fuel element surfaces, faulty welding techniques, improper facing technique, and/or contaminated shielding gas. The defects usually appear as impurities in the weld bead, aluminum oxide, dimples, pinholes, voids, tungsten oxide, and laminated or cracked caps.

Common brazing defects causing weld rejects are non-wet cans or caps, braze porosity and impurities. Contamination of the fuel element surface is usually water in the spire, oil from the lathes, and excess soap and caustic stains picked up from improperly cleaned sleeves. Water vapor is the usual shielding gas contaminate and usually results from moisture condensing in the water cooled welding torch during periods of non-use. The most frequent faulty welding techniques are insufficient or excessive shielding gas flow, damaged electrodes, striking the electrode on the fuel elements, and improper welding current. Improper facing techniques are usually a rough edge on the can O.D. and spire I.D. or an over-all surface roughness.

A typical example of a good cap and base end weld on an I & E fuel element is shown in Figure 44.

Patching by re-welding a portion of the weld bead is not permitted. However, weld reject reclamation is permitted on all fuel elements by:[76]

1. Refacing up to 0.010 inch of aluminum from the end of the fuel element with the required contour tool on a hand operated turret lathe.

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2. Removing the remaining portion of the weld bead with a 70° shoulder cut tool which cuts down the edge of the can or spire up to 0.080 inch deep and leaves a flat area at the base of the cut from 0.005 inch to 0.035 inch wide.

3. Deburring the rough edges in the welding area.

4. Brushing the welding area with a wire brush just prior to welding.

5. Rewelding in the normal manner with one weld pass.

This rewelding program has only been in operation since March 1958, but between 72 and 79 per cent of the weld rejects are reclaimed. A substantial saving (between $178,000 and $202,000 per year[76]) in materials and manpower is expected by this operation.

E. Weld Inspection

The weld is inspected visually for surface defects and irregularities since they are indicative of defects in the fusion zone or in the underlying braze layer that may lead to water entry through the weld and subsequent reactor failure. Radiographic examination of cap end weld beads are made to supplement visual exterior inspection. Some defects, however, are unresolved by X-ray techniques, such as non-wet areas that may form a continuous path through the braze layer, and therefore visual inspection is necessary. The weld is inspected following welding to eliminate any masking effects of subsequent operations. Improved lighting by using diffuse light in the weld inspection booths and good operator training have shown that visual weld inspection can be a reliable and critical inspection tool.

The weld bead is examined for:

1. Dimensional Requirements

a. Weld bead width: 1/8 inch to 7/32 inch.

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b. Weld overhang:

(1) Cap end weld: Must pass a ring gage not more than 0.010 inch larger than the maximum can O.D.

(2) Base end weld: Must pass a mandrel gage not more than 0.012 inch smaller than the minimum spire I.D.

c. Weld penetration: 0.050 inch minimum.

2. Weld Surface Defects

a. Impurities and contamination

b. Aluminum oxide

c. Moisture pits

d. Dimple

e. Incomplete can wall bonding

f. Pin hole or void

g. Tungsten oxide or electrode contact

h. Patched welds

i. Laminated or cracked caps

Other obvious defects, such as a marred surface on the weld bead or can O.D. surface greater than 0.004 inch in depth, are also rejected. Weld rejects are accumulated and grouped into special lots for weld recovery by refacing and rewelding. Other rejects are sent to core recovery.

In addition to weld inspection, a mandrel test is made on each I & E fuel element after welding and before bond and penetration testing. This mandrel test is made to prevent damaging the probe on the bond and penetration tester with spires having insufficient probe clearance. The mandrels are about two inches long and 0.012 inch smaller in O.D. than the minimum spire I.D.

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F. Bond and Penetration Testing

Fuel elements are tested for completeness of bonding using an ultrasonic bond test unit and for residual aluminum jacket wall thickness using an electromagnetic penetration test unit. I & E fuel elements are tested both externally and internally.

The bond tester detects void areas and some non-wet and brittle bond areas. These defect areas disrupt the flow of heat from the uranium core to the reactor cooling water and may result in "hot spot" corrosion failures.

The penetration tester detects areas on the fuel element where the residual aluminum wall thickness is not adequate. Considering reactor fuel element corrosion loss and magnitude of mechanical damage during reactor loading, it is estimated that 0.020 inch of can and spire wall should give adequate protection for present reactor conditions. The present Al-Si braze layer cannot be guaranteed to prevent water penetration to the uranium due to the porous structure of most braze layers.

The present bond and penetration tests, both external and internal, are done on automatic load-unload equipment installed in December 1957, with the test units contained in one tank.[77, 78] A view of a bond and penetration tester is shown in Figure 45. Conveyors feed the tanks containing the test equipment and good pieces are conveyed on to the fuel element etch machine. Reject pieces are automatically shunted to a holding station where they can either be retested or placed in reject pallets.

1. Bond Test[79, 80]

Ultrasonic bond testers are used to detect undesirable braze layer voids on the external and internal surfaces of I & E fuel elements. The external tester, which was put into production in

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January 1956, operates on a pulse echo technique and the internal tester, which has been used on all I & E production, operates on a Lamb wave technique.

In the pulse echo technique, the ultrasonic pulses, as they impinge on the jacket surface, set the jacket into resonant vibration if the jacket is not bonded to the core. At the termination of the driving pulse, the induced vibrations decay with time transmitting vibrations to the transducers. These vibrations appear at the transducer for a longer time than does a normal surface echo and thus reveals the presence of unbonded areas. A typical operating frequency is 20 Megacycles per second with a pulse repetition of 3400 per second. The fuel element rotates under water past the submerged transducer which is positioned a short distance from the element surface. Small unbonded areas which are not detrimental to the heat transfer characteristics in the reactor can be ignored by an integrator circuit. The fuel element can be rejected if the defect exceeds a prescribed circumferential length on the surface and/or if the total count over the entire surface exceeds a prescribed number.

Until April 1958, the external bond tester was adjusted to reject fuel elements with unbonded areas longer than 1.05 centimeters as measured in a circumferential direction. At that time the reject limit was tightened to 0.75 centimeter to reject any borderline fuel elements that may have been contributing to the "hot spot" failure problem. Further restrictions were imposed later when (1) a total count and/or an individual unbonded area was put into effect on enriched and normal I & E fuel elements in May and June, 1958, respectively, and (2) lengthening the memory time on the integrator circuit on enriched solid fuel elements and on part of the I & E fuel elements in May and September 1958, respectively to reject clusters of small void areas. In October 1958, all external bond test circuits were converted to the long memory method.

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The Lamb wave ultrasonic bond tester for internal surfaces requires two crystals; a sender and a receiver set in an angular position to receive signals from the braze layer. The sender excites Lamb waves in the thin laminar jacket surface over a defect. Signals can be received at rather large spacings between the crystals when over a large unbond area. Signals are also found at several crystal angles corresponding to excitation of different Lamb wave modes. This technique eliminates the surface echo by a mechanical barrier placed between the crystals and close to the spire wall surface. The fuel element rotates under water past the two crystals, which are imbedded in a probe that has been inserted into the fuel element bore. Small unbonded areas can be ignored by an integrator circuit and only unbond areas larger than a prescribed length are rejected.

Until June 1957, the internal bond tester was adjusted to reject fuel elements with unbonded areas longer than 0.5 centimeter as measured in a circumferential direction. At that time the reject limit was relaxed to 0.75 centimeter which more closely approaches the maximum allowable size of unbond areas of 0.5 square centimeter.[81]

The accuracy of the internal and external bond test is verified by testing "go" and "no-go" standards. These standards are fuel elements with known void areas.

Prior to the adoption of the ultrasonic bond test in early 1956, all fuel elements were tested for bond integrity by a "frost test" method. In the frost test method, the fuel elements are:[82]

a. Coated with a layer of acenapthene by spraying a solution of carbon tetrachloride and acenapthene on the fuel element. Acenapthene is a waxy hydrocarbon with a melting point of about 92 C.

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b. Brought to a uniform temperature of 26 ± 1 C by remaining in a constant temperature air bath for at least 20 minutes.

c. Passed through a 25 KW induction heating coil. The sprayed coating is frosty in appearance at room temperature, but melts in regions over unbonded areas on the fuel element when the piece passes through the induction coil. This is due to the unbond areas restricting the flow of heat from the jacket into the core causing a "hot spot" on the jacket surface.

d. Examined visually by an operator for any melted areas on the jacket surface.

The frost test had four major disadvantages that were alleviated by using the ultrasonic bond test. These disadvantages were:

a. The frost test was insensitive to unbond areas smaller than about one square centimeter in area.

b. Defects could not be detected near the core ends because of rapid heat transfer due to the aluminum cap and base.

c. Human error was quite possible in examining the fuel elements for melted areas.

d. The use of carbon tetrachloride was a potential health hazard for operating personnel.

2. Penetration Test[83, 84]

Electromagnetic penetration testers are used to detect undesirable thin spots, called Al-Si penetrations, in the aluminum jacket covering the Al-Si braze layer. A penetration tester for external surfaces has been used for testing production fuel elements since November 1955, and an internal penetration tester has been used on all I & E production fuel elements.

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In the penetration test, small eddy currents are induced in the fuel element jacket by electromagnetic induction. Differences in the electrical characteristics of the aluminum jacket and Al-Si braze metal affect the manner in which the eddy currents flow. Therefore, the presence of an Al-Si penetration into the aluminum jacket wall causes changes in the flow of eddy currents.

These changes in the flow of eddy current are reflected in a detector coil by electromagnetic induction. The effects of these changes in current are amplified and measured with respect to amplitude and phase. The circuit is adjusted to reject fuel elements having Al-Si penetrations with less than 0.020 inch residual can wall.

The accuracy of the penetration tester, both internal and external, is verified by testing "go" and "no-go" standards. These standards are fuel elements with known Al-Si penetration defects.

Besides the difference in electrical characteristics of Al-Si and aluminum other factors also affect the currents in the test piece, which complicates the detection problem. Such factors are:

a. Coil to test specimen spacing

b. Specimen geometry

c. Surface irregularities

d. Cracks in the aluminum jacket

e. Voids in the jacket or braze layer

f. Inclusions in or on the jacket

g. Composite structure of test specimen such as average thickness of aluminum jacket and braze layer.

In some cases, particularly in the internal penetration test, acceptable variations in the test sample may cause greater variations in the detector output than an unacceptable Al-Si penetration.

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Due to the geometry of the test piece when testing for internal Al-Si penetration rejects, the signals resulting from braze layer voids and/or spire wrinkles are magnified and result in a large number of "rejects". Since the average minimum residual spire wall thickness on these "reject" pieces is about 0.035 inch, the internal penetration "rejects" have been segregated into lots and sampled statistically for minimum spire wall thickness for lot acceptance or rejection since November 1957.

Variations in probe-to-jacket spacing is controlled mechanically on the external penetration tester by using a Teflon tape spacer between the probe and test piece. Recently a servo-actuated probe carrier was developed and is being used on part of the testers. The servo-amplifier positions the probe carrier above the surface by using an electromegnetic coil. To scan the external surface the fuel element rotates past the external test coils under water with the test coils riding on the Teflon tape spacer or automatically spaced with the servo-probe unit.

The internal penetration test coils are embedded in the same probe containing the internal bond test crystals. The internal surface is scanned under water by having the fuel element rotate past the probe that has been automatically inserted into the fuel element bore.

Prior to the use of the penetration tester in 1955, the only check on minimum can wall thickness was an occasional destructive examination (about one fuel element per shift per day). The braze line inspection after facing was used at that time for detecting and correcting abnormal canning conditions that resulted in gross Al-Si penetrations.

The destructive examination for minimum can wall thickness was by machining down to the Al-Si in small increments or more accurately by etching and dissolving the aluminum can wall in

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caustic. The etching reveals Al-Si as a black spot on the can surface. This etching method is still used for destructive examination for minimum can wall thickness.

G. Fuel Element Etch

The fuel element is degreased and etched after bond and penetration testing to remove any foreign materials from the can surface that may start localized corrosion in service. Etching also leaves a clean surface for the formation of a uniform autoclave film.

Prior to the use of the present automatic etch machines (See Figure 46) in late 1955, the degreasing and etching operations were done by a batch-wise hand operated method. The degreasing is done in a vapor degreasor using stabilized trichloroethylene, which removes any grease, oil and acenaphthene (when the frost test was used), to assure a uniform etching action. Hot (80 to 90 C) nitric acid is used as the aluminum etchant. The nitric acid concentration averaged about 60 per cent and the etch time about five minutes for the batch operation, but the use of this concentration and time led to corrosion problems and large nitric acid losses in the automatic machines. To relieve these problems the acid concentration was reduced to 15 to 30 per cent and the etch time was increased to 10 to 15 minutes with no loss in etching properties.[54]

Following etch, the fuel elements are rinsed in two cold and one hot water rinse and dried in a forced air dryer at 40 C minimum.

The amount of aluminum removed during etching is less than 0.0005 inch and the maximum number of times that a fuel element can be etched is two. Fuel elements that do not etch clean or that have stains and inclusions after autoclaving are usually re-etched.

There was difficulty with the as-received automatic machines due to copper contamination which may have contributed to the

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high inclusion reject rate in early 1956. The copper contamination was reduced by replacing the brass parts on the machines with other materials.[28]

H. Autoclave Test

The autoclave test partially simulates reactor conditions and can detect unsound closures and jackets if the defects are continuous from the exterior surface to the core. Defective elements are detected due to the rapid attack of the uranium core by water or steam and since the increased volume of the reactor products ruptures or swells the jacket. The autoclaving also forms an oxide film on the fuel element that increases the abrasion resistance. Some localized corrosion areas on the jacket are also disclosed during autoclaving by darkened or haloed areas called inclusion rejects.

The present autoclave method is to autoclave fuel elements in steam or water at 90 to 125 pounds per square inch and 165 to 185 C for a minimum of 20 hours. Prior to August 1957, the autoclave time was for a minimum of 40 hours.

About 72 eight inch normal uranium fuel elements are loaded in each autoclave basket with six baskets per autoclave. The baskets have aluminum spacers to separate the individual fuel elements and a Teflon plate on the bottom to prevent marring the weld bead on I & E fuel elements.

As the fuel elements are loaded in the baskets, they are examined briefly for obvious defects, such as marred surfaces, weld defects, surface inclusions, and improperly etched pieces which are removed from the process stream. During periods when large numbers of pinhole rejects and cap non-wets are prevalent (as in October 1958), another cap weld inspection is made after the fuel elements are placed in the autoclave baskets. Six loaded baskets are stacked on a spider and loaded and unloaded in one of 36 available autoclaves by an overhead crane which hooks onto a shaft fastened to the spider and extended

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up through the center of the six baskets. Only about three feet of the eight foot long autoclaves extends above the floor surface as shown in Figure 47.

Prior to the use of the present autoclaves in the 313 Building in early 1955, steam autoclaves were used in the 314 Building for autoclaving all fuel elements. A large amount of material transferring was obviously necessary with this arrangement.

When the first major inclusion reject problem arose in 1955, the autoclaves were investigated as a source of the inclusions. To reduce possible inclusions, an autoclave cleaning method was developed and tested.[85] The autoclaves were de-scaled with an inhibited hydrochloric acid compound (Oakite 32) and coated with a phosphate rust inhibitor (Turco 3557) which was sealed with a dilute sodium chromate solution. This method produced clean autoclaves, but unfortunately this did not solve the inclusion problem and the cleaning program was stopped. It was later found that copper contamination from the automatic cleaning machines was the major source of inclusions and was only apparent after autoclaving.

I. Final Fuel Element Inspection

After autoclaving the fuel elements are removed and inspected to detect and reject any elements that (1) failed the autoclave test, (2) are dimensionally unsuitable, and/or (3) have excessive surface damage, inclusions, stains, or other abnormalities.

Tube and mandrel gages are used for the dimensional inspection of the fuel element. The tube gage, which has an I.D. 0.015 inch larger than the maximum as received can O.D. and is longer than the fuel element, rejects any pieces that may restrict water flow through the annulus of the process tube. The mandrel gage, which is a ball mandrel 0.012 inches smaller in diameter than the minimum as received spire I.D., rejects any I & E elements that have a flow restriction in the fuel element bore.

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A visual inspection of the fuel element surface completes the final inspection operation. This visual inspection includes the following types of rejects:

1. Marred surfaces
   a. Any damage to the cap or base that will prevent fuel element mating.
   b. Any scratch or dent greater than 0.004 inch in depth on the weld area or on the thin can and spire wall surface.
   c. Any scratch or dent greater than 0.010 inch in depth on the cap end of the fuel element.
   d. Any scratch or dent greater than 0.035 inch in depth on the base end of the fuel element. This permits proper stamping yet ensures adequate aluminum coverage.
   e. Any dent or marred area on or extending through the base bevel having a circumferential dimension greater than 3/8 inch and a depth greater than 0.004 inch. This restriction is included for determining whether a fuel element has been dropped or mishandled with the possibility that the compound layer has been fractured.
2. Any swelling, wrinkling or rupture of the jacket except slight wrinkling of the I & E spire.
3. Corrosive pitting, stains, or embedded foreign material (inclusions).
4. Any Al-Si on the fuel element surface.
5. Cap or can defects such as seams, laminations or holes.
6. Any weld defects such as poor bonding, pinholes, porosity and cracking.
7. Any unusual appearance of the fuel element such that the quality is questionable.

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Fuel elements rejected for stains, abnormal oxide coating, and small inclusions are segregated into special lots and re-etched and re-autoclaved.

At final inspection, a sample is taken from each lot for reactivity testing in the Hanford Test Reactor. Eleven pieces of eight-inch normal uranium fuel elements, 22 pieces of four-inch normal uranium fuel elements, and six pieces of enriched uranium fuel elements are needed for accurate reactivity testing of the particular type of fuel element being tested. In addition to maintaining minimum acceptable reactivity, lot shipments to the reactors are arranged to avoid accumulation of sub-average lots in any one reactor.

When cored fuel elements were being fabricated, they were examined at final inspection for any lead or Al-Si that may have leaked into the interior of the core. This testing was done using a gamma ray core tester, which passed a collimated gamma ray beam from a Co^{60} source axially through the core bore to a scintillation detector.[86] A decrease in radiation intensity by the absorption of the gamma rays in lead and Al-Si was used to detect these materials in the core hole. Any cored fuel elements with as little as a 1/4 inch drop of metal in the bore was rejected.

Before the completion of the expansion of the 313 Building in early 1955, the final inspection station was in the 303A Building which presented a material handling problem.

J. Radiograph Test

The cap end weld on all uranium fuel elements is radiographed to detect voids in and under the weld bead that cannot be seen by a visual surface inspection. These defects, if large enough, could allow water entry to the uranium core if the weld bead was damaged or eroded away in the reactor.

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The radiograph test was developed in 1952,[87] but was not established as part of the standard process until after installation of two radiograph machines in the 313 Building in early 1955.[88] The radiograph machines were first installed immediately following the fuel element etch machines, but were later moved to the present location behind the final inspection station (See Figure 48). This relocation improved the flow of material through the finishing area since there is a minimum delay at radiographing of about 20 minutes while the film is being processed and read.

Eighteen fuel elements are radiographed at the same time in a hand loaded holder that automatically rotates the pieces 120° between exposures. The elements are inclined at an angle of 30° from the X-ray source. The radiograph conditions are:

1. Voltage: 100 ± 2 kilovolts, peak.
2. Amperage: 7-1/2 ± 1/2 milliamperes
3. Focal distance: 54.0 inches ± 0.5 inch
4. Exposure time: 6 to 9 seconds
5. Number of exposures: Three exposures of each weld at 120° rotation.

After the film is exposed, the fuel elements are removed from the holder and placed in storage pallets in a known position to await film processing through an automatic developer. The films are visually inspected using a fluorescent film viewer and the reject pieces removed from the pallets and sent to core recovery.

The pieces are rejected due to the following type of defects:

1. Individual voids, grouped voids, or porosity masses (a) greater than 1/2 the distance from the core to the outer edge of the weld bead, or (b) greater than 3/8 inch long. Voids and/or porosity masses adjacent to each other within the width of the radiograph are considered together. Porosity masses include more than two voids less than 1/32 inch in diameter grouped less than 1/32 inch apart.

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2. Any void regardless of size that shows no visible weld bead cover on the radiograph film. Heavy metal inclusions, mainly compound layer particles, in the braze line and weld are not rejected.

The present reject rate for radiographic inspection is about 0.3 per cent. This is not large, but based on the severity and size of some of the voids found by destructive examination of radiograph rejects, this inspection probably prevents several ruptures per year in the reactors.[89]

The base end weld on I & E fuel elements are not presently radiographed but equipment is being developed in case it is found desirable. The base end weld is not considered as critical as the cap weld since any entrapped air or other gasses will tend to rise and accumulate near the cap end of the assembly.

One of the proposed methods for radiographing base welds on I & E elements was to insert a thulium-170 soft gamma radiation source into the hole through the cap end of the fuel element. By positioning the source properly, the gamma radiation penetrates the weld area and exposes a film. An experimental machine was built[90] and the thulium-170 source was tested on over 1000 pieces in 1957. This method, however, was unsatisfactory, since it was not sensitive enough to detect small voids due to the short focal length or lack of a point source, and was discontinued. The thulium-170 also had a short half life (129 days) making it necessary to replace the source frequently and was a potential radiation hazard.

Another method for radiographing male welds, which is now being developed, is to use a fuel element holder with a 65° angle from the X-ray source. This will permit the X-rays to pass through the male weld when the elements are positioned base end down. The same holder can be used for the cap weld by positioning them cap end down and taking another radiograph.

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A faster radiographing method, the TVX, was investigated in 1956, but did not have sufficient resolution for our use.[91,92] The TVX method uses a conventional X-ray source, but the image is picked up on a photo-conductive X-ray pickup tube and transmitted to a television receiver in any desired remote location. The resolution is limited due to the size of the electronic scan beam, the focal length between the source and pickup tube, and the small number of scanning lines.

Other types of radiography are also being investigated, such as xeroradiography and image intensified fluoroscopy which are described in Section V, M.

K. Fuel Element Storage

The finished fuel elements are loaded and stored in 200 or 300 hole pallets as shown in Figure 48. The pallets must be kept dry and clean to prevent corrosion or contamination while in storage. A rubber lining is used on the pallet floor for fuel elements stored weld end down to prevent marring the weld bead.

Fuel elements stored longer than three months are re-inspected for surface corrosion before being transferred to the reactors. Also, before the fuel element lots are transferred to the reactors, the reactivity values for the bare cores and the finished fuel elements must be obtained and reviewed.

The present fuel elements are stored in either storage bays in the 313 Building or in 303 hutments.

L. Material Transfer and Handling

The fuel elements are transferred from the various finishing and inspection operations by the following methods:

1. By 66 hole pallets on hand trucks from the quench tank to the facing lathes.

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2. By "skate-wheel" and "drag-chain" conveyors from the lathes to the fuel element etch machine where they are loaded by hand on the cleaning racks.

3. Loaded by hand from the etch machine racks into autoclave baskets.

4. The autoclave baskets are handled and loaded and unloaded into the autoclaves by an overhead crane.

5. Autoclave baskets are handled on roller conveyors at the final inspection station as shown in Figure 49.

6. Empty autoclave baskets are returned to the etch machines on a newly installed roller conveyor,[93] as shown in Figure 49.

7. Fuel elements from final inspection are conveyed to the radiograph machines on "skate wheel" conveyors.

8. After radiographing, the pieces are placed in storage pallets that are handled on roller conveyors, as shown in Figure 48, until they are moved to storage by high lift trucks.

9. All other fuel element movements, such as pieces to core recovery, the test reactor and to the Pilot Plant are handled in storage pallets by high lift trucks.

M. Finishing and Inspection Development Programs

1. Automatic Lathe Unload and Length Check Mechanism

An automatic lathe unload system which has a built in length checker has been designed and the prototype equipment should be finished by January 1959. This unloader transfers the ejected fuel elements from the lathe collets to an automatic length checker. If the piece is either too long or too short, it is shunted to a reject conveyor and if it is within length limits it is transferred to a "skate-wheel" conveyor for transfer to the next station.

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2. Automatic Stamper

An automatic stamper is being designed to stamp the fuel elements after they have been base end faced. The stamper will be installed in the conveyor line immediately following the automatic lathe unload and length check mechanism. The prototype stamper is expected to be completed by the third quarter FY 1959.

3. Automatic Welders

Five fully automatic welders are being installed in the 313 Building. The welders are fed and unloaded automatically on "skate-wheel" conveyors. The pieces pass through an automatic buffer that brushes the weld to permit easier arc starting before being welded. The buffers will have an exhaust system to remove the fine aluminum dust which might contaminate the fuel element surface or be a fire hazard. The automatic welders should be completed in January 1959.

4. Attaching Water Mix Spools

A welding method was developed in the Pilot Plant for attaching the aluminum alloy water mix spools (See Figure 8) to the base end of six-inch normal uranium I & E fuel elements. The spools are welded on by an inert gas shielded metal arc welding procedure with consumable 4043 aluminum alloy electrodes. The fuel element and spool are rotated horizontally in a lathe while being welded. Welding equipment for attaching water mix spools in the 313 Building should be completed in January 1959.

5. Automatic Mandrelizer

An automatic mandrelizer is being designed to mandrel test all I & E fuel elements before bond and penetration test. It is planned to install the mandrelizer on the "drag-chain" conveyor in the weld inspection area. The prototype is expected to be completed during the third quarter of FY 1959.

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6. Bump Discriminator for Penetration Tester

An internal penetration test bump discriminator (BD) probe and electronics has been developed and tested which could eliminate the statistical sampling of internal penetration "rejects" and assure a better quality product for the reactors. The BD probe can be used on the present testers with no additional complications but for best results the BD electronics should also be used with the BD probe. Since the BD electronics are quite complicated, it is planned to convert all testers to the BD probe and to save the "rejects" and retest them using BD electronics.

7. Mandrelizing Internal Penetration Rejects[94]

A method has been developed for recovering about 63 per cent of the internal penetration "rejects" by pulling a steel ball mandrel through the I & E spire. The ball mandrel is only about 0.002 inch larger than the average spire I.D. but it is sufficient to smooth out the small wrinkles and bubbles without reducing the residual spire wall thickness. After mandrelizing, the pieces are retested on the internal penetration tester and the pieces rejected this time are sent to core recovery.

Before adopting this procedure, the effect on the internal bonding layer, male weld, and spire wall must be further evaluated.

8. External Lamb Wave Bond Tester

Research is being done on using a Lamb wave bond test for external bond testing. This two crystal method is now being used on the internal bond test. This technique is described in Section V,F,1. When developed the external Lamb wave tester will be compared with the present pulse-echo method. If it improves the bond test, it will be adopted as the standard external bond test.

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9. Automatic Fuel Element Etch Machine Loader[95]

A prototype automatic etch machine loader was built and tested in early 1958. This loader automatically loaded eight-inch fuel elements in the etch machine baskets. The loader was fed by two "skate-wheel" conveyors from the bond and penetration test area.

It was found that further development work would be necessary before the loader would be practical. This includes:

(a) More accurate positioning of the etch machine baskets at the loading position.

(b) The present etch baskets vary too much in dimensions and alignment to be used and new or improved baskets would be necessary.

(c) Further modifications are necessary to handle six-inch fuel elements.

(d) Better precision is necessary on some parts of the loader for accurate alignment.

At the present time it is doubtful that the automatic loader will be used due to the cost of the above needed changes and to the possibility of replacing the present etch machines by a simpler process.

10. Replacement of the Fuel Element Etch Machine

A new simpler fuel element etch process is being investigated to replace the present etch process. Present plans are to: (1) use an alkaline etch followed by a dilute acid neutralizing solution in place of the present 15 to 30 per cent nitric acid and (2) use a "straight-through" conveyorized machine.

The present machines are expected to have only a service life of two to three years more and a large amount of maintenance is now required to keep them operating. Also, the present process

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does not adequately remove copper inclusions from the aluminum surface but does remove any iron inclusions. Any new process used should be one that will remove copper inclusions.

The new process and etch machine are expected to be completed during FY 1960.

11. Inclusions Problem[96, 97]

Inclusions are foreign materials embedded in or alloyed with the aluminum jacket and are revealed by autoclaving and rejected at final inspection. The inclusions are visually black and some have a halo area around the inclusion. Most inclusions are very small, averaging around 0.015 to 0.020 inch in diameter. A rejectable inclusion is one which is 0.010 inch in diameter or any inclusion which has a halo. Inclusions less than 0.035 inch in diameter are re-etched and re-autoclaved.

The inclusion problem may be separated into two categories:

a. Incident inclusions where reject rates rise very rapidly (usually beyond 40 per cent) endure for a short period of time and then drop to background rate.

b. The background inclusion rate which is usually less than five per cent and is always present.

Particles of sand, M-388 aluminum, and stainless steel have undoubtedly been contributing to the background inclusion reject rate. During the past year, however, it was found that in almost every case the high incident inclusions were caused by a copper bearing material from the component preparation area or a large amount of sand in the process water. Other possible sources of inclusions are: (1) airborne sand and fly ash, (2) inclusions present in the as-received components, (3) material on new sleeves, (4) particles embedded by the lathe collets, (5) arcing between the

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silver contacts and the fuel element during welding, (6) autoclaves, and (7) undissolved particles of Al-Si and can alloy remaining on the sleeves after sleeve preparation.

Development work is continuing on reducing the inclusion reject rate by: (1) finding and eliminating the source of the inclusion, (2) removing inclusions during fuel element etch, and (3) detecting incident inclusions early before large numbers of pieces are canned.

12. New Radiograph Trays[98]

A new radiograph tray has been prototyped, tested, and production quantities ordered to replace the present trays. The new trays hold the fuel element at an angle of 65° from the X-ray source rather than at 30° from the source, which will permit the base weld to be radiographed if desired. The new trays will also hold 20 rather than 18 fuel elements, require less maintenance, and can handle either film or xeroradiograph plates.

The new trays should be in use by February 1959.

13. Xeroradiography[99]

Xeroradiography has been tested on a limited scale as a replacement for the present radiograph method. The results appear promising but a large scale test will be necessary before any decision can be made. This large scale test is awaiting the arrival of the new radiograph trays which can handle the xeroradiography plates.

Xeroradiography is a process that can provide a viewable image within one minute after radiographing. The normal radiograph film is replaced by a selenium coated plate which has an electric charge on its surface. When radiation strikes this plate, the charge leaks away in proportion to the amount of exposure. Thus, during radiographing the electric charge is strongest beneath the densest material. This latent image is made visible by dusting with a white

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powder that is attracted to the charged area. After inspection of the image, the powder is removed, and the plate is recharged and used again. With care, 1,000 exposures per plate should be attained.

Some of the advantages of xeroradiography are:

a. Elimination of the lag storage period between exposures and film reading. This is 20 to 60 minutes for the present process and the pieces must be stored in a carefully oriented manner so that defects on the film can be related to the proper fuel elements. With xeroradiography, the image is available within one minute after exposure and the rejects can be removed while the fuel elements are still in place on the radiograph trays.

b. Space utilization. The xeroradiography unit occupies about the same floor space as an office desk and would eliminate the darkroom, making that space available for other uses.

Some of the disadvantages of xeroradiography are:

a. Plate cost. Each plate costs about $350 and at least 1,000 exposures must be made on each one before they can compete economically with film.

b. Plate memory. For best results the plates should stand for at least an hour between exposures to completely discharge the plates. If not, the first image will appear as a double exposure after the second exposure. This plate hold-up requires the use of a large number of costly plates.

c. Plate cleaning. Dirt, dust, hand prints, and other contamination must be removed or it will interfere with the image. To clean the plates requires the utmost care using distilled water and a mild detergent to prevent damage to the selenium coating. This cleaning process is not a production type process.

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14. Image Intensified Fluoroscope

An image intensified fluoroscope is being investigated as a method of detecting voids in and under the weld bead. Direct examination of each fuel element would be possible with this process thereby eliminating any film or plate development processing time. The grain size of the phosphor may limit the resolution obtained.

VI. Core Recovery

Between 10 and 30 per cent of the fuel elements canned do not meet specifications and are rejected. These rejected fuel element cores are recovered by a chemical process and prepared for recanning. The recovery operation results in a loss of uranium from the core and the reactivity is controlled by establishing a minimum acceptable core weight. The canning cycle induces some dimensional changes in the cores due to the thermal treatment received in the molten baths. Diameter and length changes are not significant, but eight-inch cores warped in excess of about 0.020 inch are not readily assembled and may damage the can during insertion.

The core recovery is a batch operation with about 768 eight-inch fuel elements being processed at one time in the "stripper" and "treater" tank. The reject cores are handled in six baskets by an overhead crane and monorail. Up to four batches of cores can be processed in a two shift operation per day.

A. Aluminum Jacket and Braze Removal

The aluminum jacket and most of the Al-Si braze metal is removed from canned reject fuel elements in a caustic solution. The solution used is a 14 to 20 per cent sodium hydroxide and 10 to 15 per cent sodium nitrate solution. The solution is kept at the boiling temperature in the "stripper" tank during the jacket removal which usually takes about two hours. After jacket removal, the solution

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is drained from the tank and the cores hosed down with water before being transferred to the compound layer removal or "treater" tank.

The sodium nitrate is used in the solution to convert the hydrogen released by the reaction between aluminum and sodium hydroxide to ammonia gas which is vented to a stack.

The reject I & E fuel elements that are plugged with Al-Si are treated in a molten Al-Si bath to remove the plug before being processed in the "stripper" tank. Since there is a possibility of water in the bore, the agitator, which lowers the fuel element into and out of the molten Al-Si in the furnace, is covered to protect the operator from any Al-Si eruptions.[100] The cores are water quenched after removal from the Al-Si bath and transferred to the core recovery area.

Prior to the adoption of this recovery process for plugged cores in April 1958, the plugged cores were: (1) sent through the normal core recovery process, (2) the plugs were removed by drilling, and (3) sent through the core recovery process again. This method resulted in a large number of core rejects, high machining costs, and excessive uranium losses in the recovery operation.

B. Compound Layer Removal

Following the aluminum jacket removal, the compound layer and the remainder of the Al-Si braze metal is removed from the cores in a concentrated caustic solution in a "treater" tank. The solution used is above 50 per cent sodium hydroxide and is maintained at 150 to 170 C during the reaction time of two to three hours. The reaction time should be as short as possible to prevent uranium loss but long enough to remove the compound layer.

After the cores have been removed from the "treater" tank, they are placed in an automatic rinse tank for rinsing. This automatic rinse tank, which was installed in mid 1957, is an enclosed vented

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tank with provisions for saving the uranium sludge washed from the cores.[101] The previous rinse method was by hose spraying and dipping in an open tank. The new method also reduced uranium contamination of the operators and work area and reduced the safety hazard present with caustic solutions. The cores are dryed by setting in air after removal from the rinse tank.

The same caustic solution is used, with make-up additions, until about 16,000 normal uranium fuel elements or 12,000 enriched uranium fuel elements have been processed through the "treater" tank.

The caustic method of compound layer removal replaced the previous hydrofluoric and nitric acid method in 1953.[102] The previous method was: (1) a 10 per cent hydrofluoric acid etch at 25 or 35 C for about three hours, (2) water rinse, (3) a 20 per cent nitric acid etch at 70 to 80 C for about one hour, (4) water rinse, and (5) dry in air. This method was more expensive, not as simple, and not as safe as the caustic method. In fact, the use of hydrofluoric acid presented a hydrogen explosion hazard from the hydrogen released in the reaction between HF and the core.[103]

C. Recovered Core Inspection

Recovered uranium cores are inspected to assure an acceptable quality level. The core weight is controlled to assure sufficient reactivity in any lot of recovered fuel cores. All recovered cores (except for cores that have only been recovered once and can be identified) are weighed individually and the underweight cores scrapped. Any core that has reached the minimum weight limit has probably been through the recovery cycle at least three times.

The minimum weight for an eight-inch solid and an eight-inch C size I & E core is 0.14 and 0.21 pounds less, respectively, than the bare virgin core weight. After each canning-recovery cycle the core dimensions change approximately as follows:

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1. 0.003 inch O.D. decrease
2. 0.006 inch I.D. increase
3. 0.003 inch length decrease

The recovered cores are grouped into lots and sampled statistically for warp (maximum 0.020 inch single throw) and incomplete removal of compound layer. Warp rejects and any obvious surface defects such as cracks and large seams are scrapped. Pieces with incomplete compound layer removal are recycled through the "treater" tank.

D. Uranium Recovery

The uranium dissolved in the nitric acid pickle and caustic "treater" solutions is recovered by pumping the two solutions into a common "neutralizer" tank. The resultant solution, when neutralized, precipitates the uranium mainly as sodium diuranate. The precipitate is removed by filtering the slurry in a plate-and-frame filter press. The filtrate or "C-6" sludge is collected in metal drums and returned to the uranium core fabricators for final recovery.

The uranium sludge collected from the automatic rinse tank is also added to the "neutralizer" tank and the uranium recovered.

Massive uranium scrap such as underweight cores or pickle rejects are returned to the uranium core fabricators in the same wooden boxes that virgin cores were received. Fine uranium scrap such as turnings are returned to the fabricators submerged in water soluble oil in metal drums.

E. Core Recovery Development Programs

All of the core recovery development programs are directed toward saving uranium scrap losses. It is estimated that this loss will amount to $1,500,000 during FY 1959 and seventy to eighty per cent of this loss results from the core recovery process.(104) The present development programs are:

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1. Short Treater Time[105]

The caps and can bases take an excessively long time to dissolve in the caustic as compared to the spire and can walls. At the present time the cores are transferred from the stripper to the treater tank with some residual cap and can base undissolved and this residual material is removed in the treater solution. The extra time necessary in the treater tank to dissolve the caps and can bases removed more uranium than is necessary from the remainder of the core. The stripper solution does not dissolve any appreciable amount of uranium if the cores are left in until the caps and can bases are dissolved. This then allows a shorter time in the treater tank to remove just the compound layer.

Further work is being done on this technique to determine more fully the uranium weight savings and the optimum time in the stripper and treater solutions for each type of fuel element.

2. Mechanical Cap and Can Base Removal

Several mechanical methods of removing caps and can bases have been developed on a laboratory scale over the past several years but none have proven successful for production. If the caps and can bases could be removed mechanically it would shorten the time in the stripper and treater tank with less uranium losses. Therefore, investigations are continuing on methods of mechanical cap and can base removal.

3. Melt Recovery and Direct Re-Canning[104]

A melt recovery and direct re-canning process is under development to replace the present chemical recovery process. If successful, this new process would eliminate about 85 per cent of the uranium scrap from the production area. In this method the fuel elements are recovered by melting the aluminum jacket and braze material from the core in a molten metal and transferring

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the cores directly to the duplex bath for recanning. This not only eliminates the chemical recovery process but also eliminates the core pickle and inspection operations. It would take about 18 months to complete the development and installation of equipment for this process.

4. Stripper Tank Recovery

An investigation is being made on using only the stripper tank for core recovery. The compound layer will be left on the core and after an acid pickle the core will be recanned.

VII. Nuclear Safety[106]

Precautions are necessary during storage or handling of enriched uranium to prevent a nuclear chain reaction. The number of fuel cores necessary for a chain reaction varies with such conditions as U^{235} enrichment, core geometry, core arrangement, the presence of a moderator such as water or wood, and the presence of other fissionable material and reflectors such as natural uranium and other enriched uranium.

The only enriched uranium fuel elements now handled in production quantities are six inch long 0.94 per cent U^{235} uranium fuel elements in solid and "C", "K" and "O" size I & E form. In the past, other enriched uranium and enriched uranium-aluminum alloys have been canned in production and production test quantities. Some of these other enrichments were:

1. Enriched uranium cores containing 1.25, 1.44, 1.60 and 1.75 per cent U^{235}.
2. Enriched uranium-aluminum alloy cores containing 4.5 and 7.5 per cent enriched uranium that contains at least 92.5 per cent U^{235}.

The handling and storage limits of enriched uranium have been calculated on two conditions:

1. The limits are based on the most favorable condition for nuclear reaction possible.

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2. The limits are based on fixed piece spacing and the amount and spacing of the moderating materials. These limits are less restrictive than the preceeding one since it is possible to avoid the favorable conditions for nuclear reaction by design.

Some examples of the limits for the storage, handling and processing of 0.94 per cent enriched six-inch uranium fuel elements are as follows:

1. The maximum density of enriched and normal uranium cores in the 313 and 306 Building in any rectangular volume of unlimited height that is four feet in each lateral dimension shall not exceed 450. Natural uranium can be stored in concentrations exceeding this value if a six foot separation is kept between the enriched and natural uranium.

2. The maximum number of enriched fuel elements in an autoclave is 360. (This compares to 432 for eight-inch normal pieces.)

3. During core recovery the maximum number that can be processed at one time is 672 with not over 96 pieces in the two top-center baskets. (This compares to 768 for eight-inch normal pieces) The maximum number of enriched pieces processed through one treater solution is 12,000.

4. Enriched uranium is usually stored in 303 hutments in one of the three following arrays (10 feet separation is required between arrays):

   a. Pieces can be stored in any container but the layer shall not exceed 10 inches in height. Horizontal spacing is optional.

   b. Pieces stored in 200 and/or 100 hole pallets shall not exceed two layers in height with optional horizontal spacing.

   c. Pieces stored in 100 hole pallets can be stored in rows not to exceed three layers in height with a minimum of one foot between rows.

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5. Miscellaneous enriched scrap, turning and sludge are stored and shipped in 30 gallon barrels in a one layer array with not over 200 pounds of uranium per barrel.

VIII. Fuel Element Pilot Plant[107]

In May 1957, the fuel element Pilot Plant (306 Building) began operation and provided HAPO with the first facility devoted exclusively to developing and piloting the fabrication of better reactor fuels. This facility is comparable in size and scope to one complete regular manufacturing fuel element canning line and includes complete facilities for component preparation, canning, finishing, and all inspections except autoclaving. The Pilot Plant, with a floor space of 7200 square feet, has a potential capacity of 40 tons per month on a one-shift basis. Several views of the Pilot Plant are shown in Figures 50, 51 and 52.

The primary use of the Pilot Plant has been to develop improved canning procedures for I & E fuel elements and to reduce the "brittle-bond" problem. Present development plans in the Pilot Plant are to improve bonding, reduce braze porosity, and eliminate can and spire non-wetting.

In the third quarter FY 1959, the lead dip canning Pilot Plant development work may be transferred to the 313 Building. This will permit the installation of co-extrusion cladding equipment in the Pilot Plant for development of Zircaloy-2 clad uranium fuel elements for the NPR reactor.

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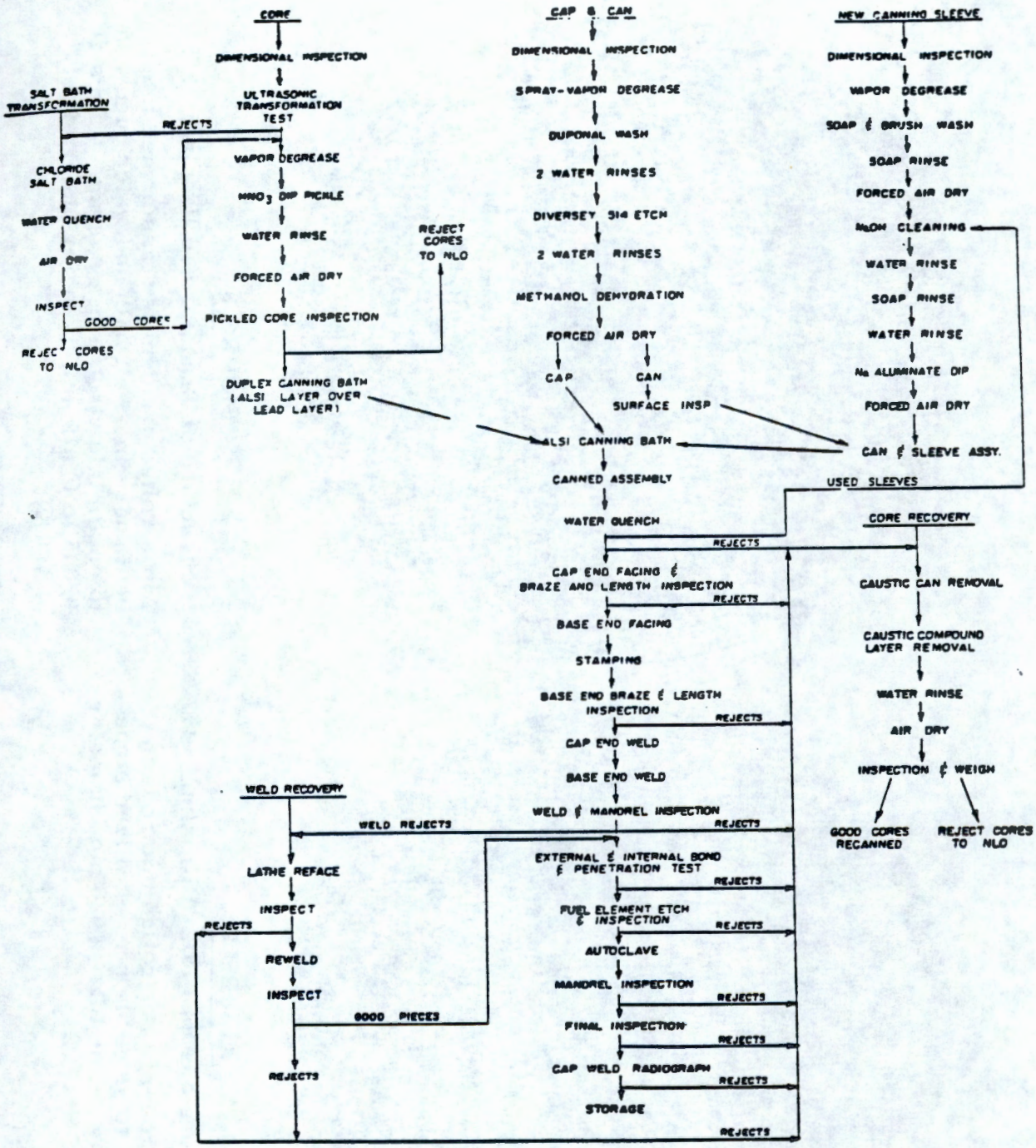


FIGURE 1

HAPO Lead Dip Canning Process

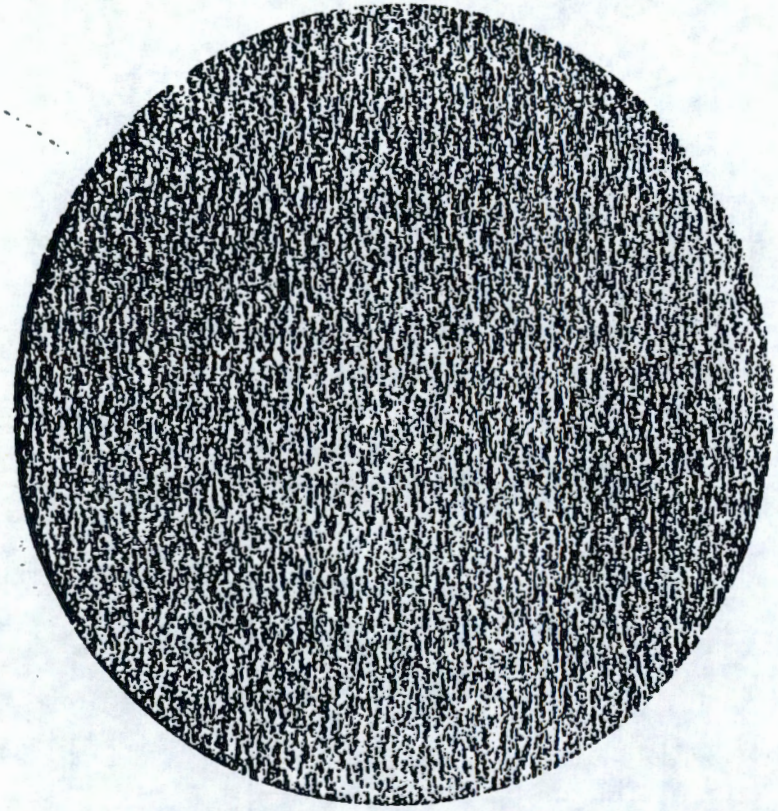


FIGURE 2

Structure of Alpha Rolled Uranium 3X

Uranium ingots are hot-rolled into rods in the alpha phase to give this recrystallized structure. Average grain size 0.020 mm diameter (determined at 100X)

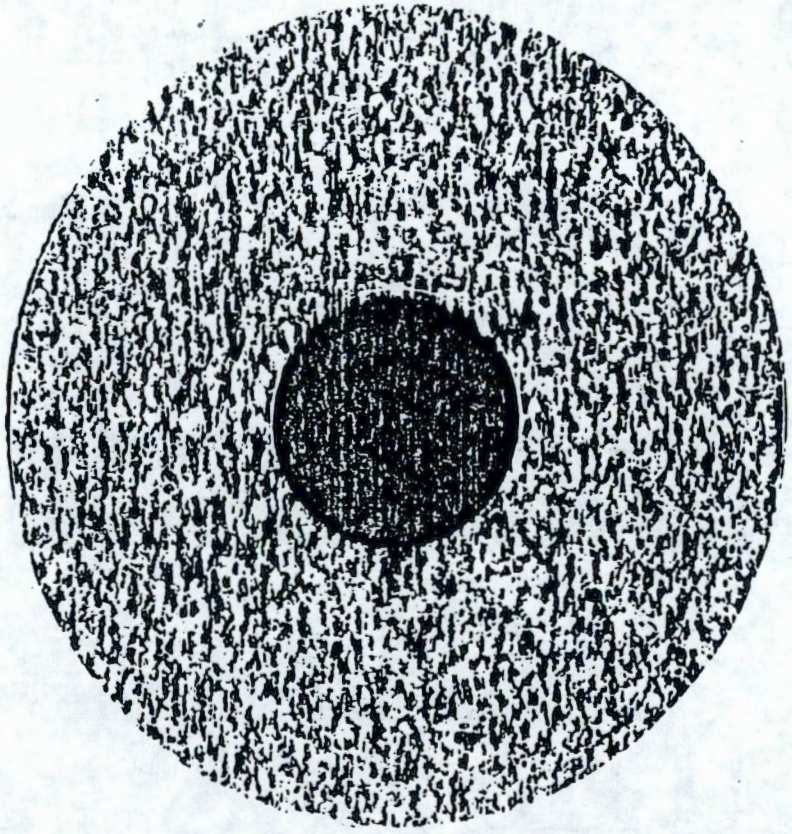


FIGURE 3

Structure of Transformed Uranium 3X

Alpha rolled uranium is transformed into the beta phase in a salt bath and water quenched to obtain this structure. Average grain size 0.065 to 0.075 mm diameter (determined at 100X)

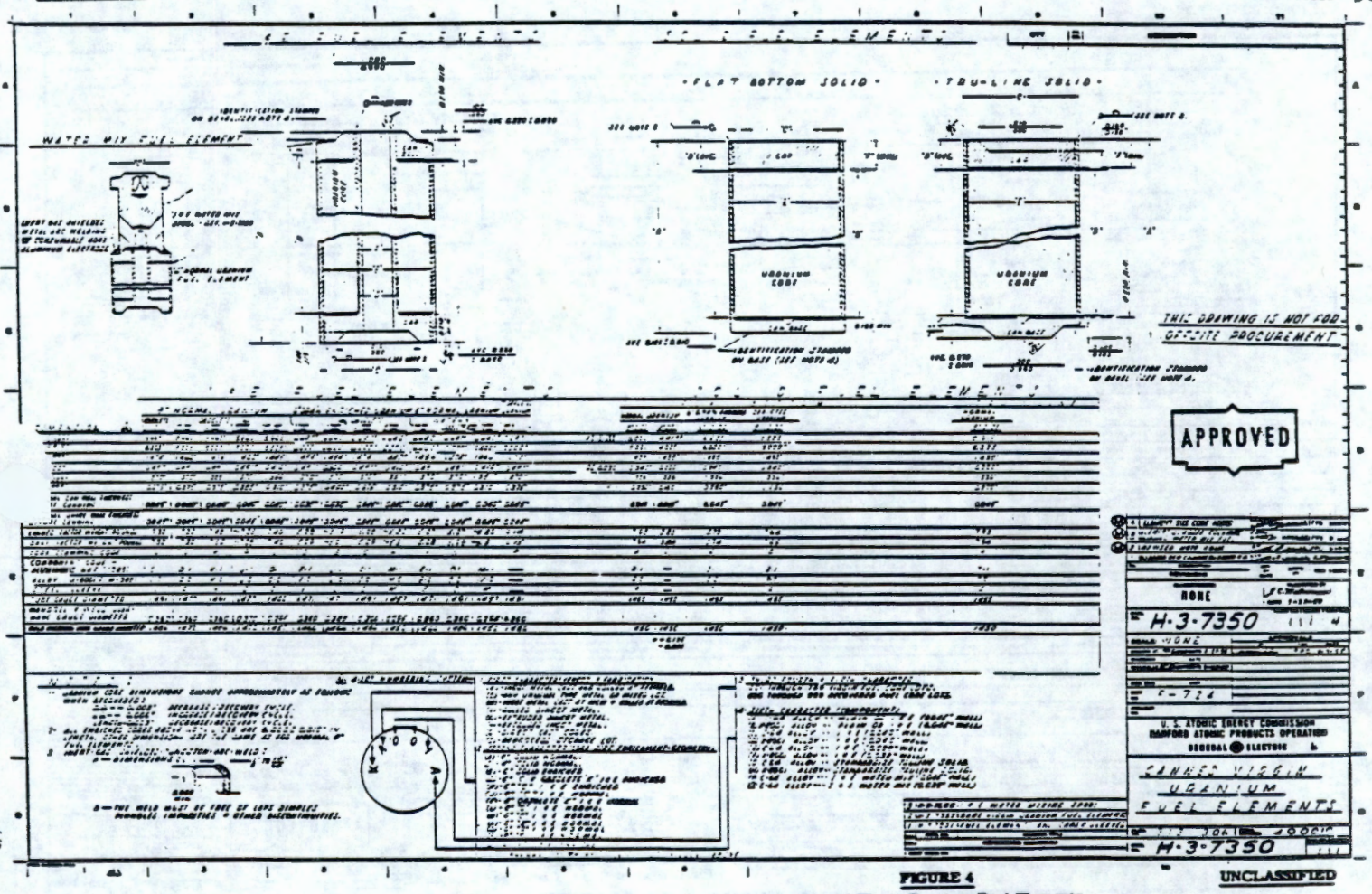


FIGURE 4

Canned Waste Uranium Fuel Elements

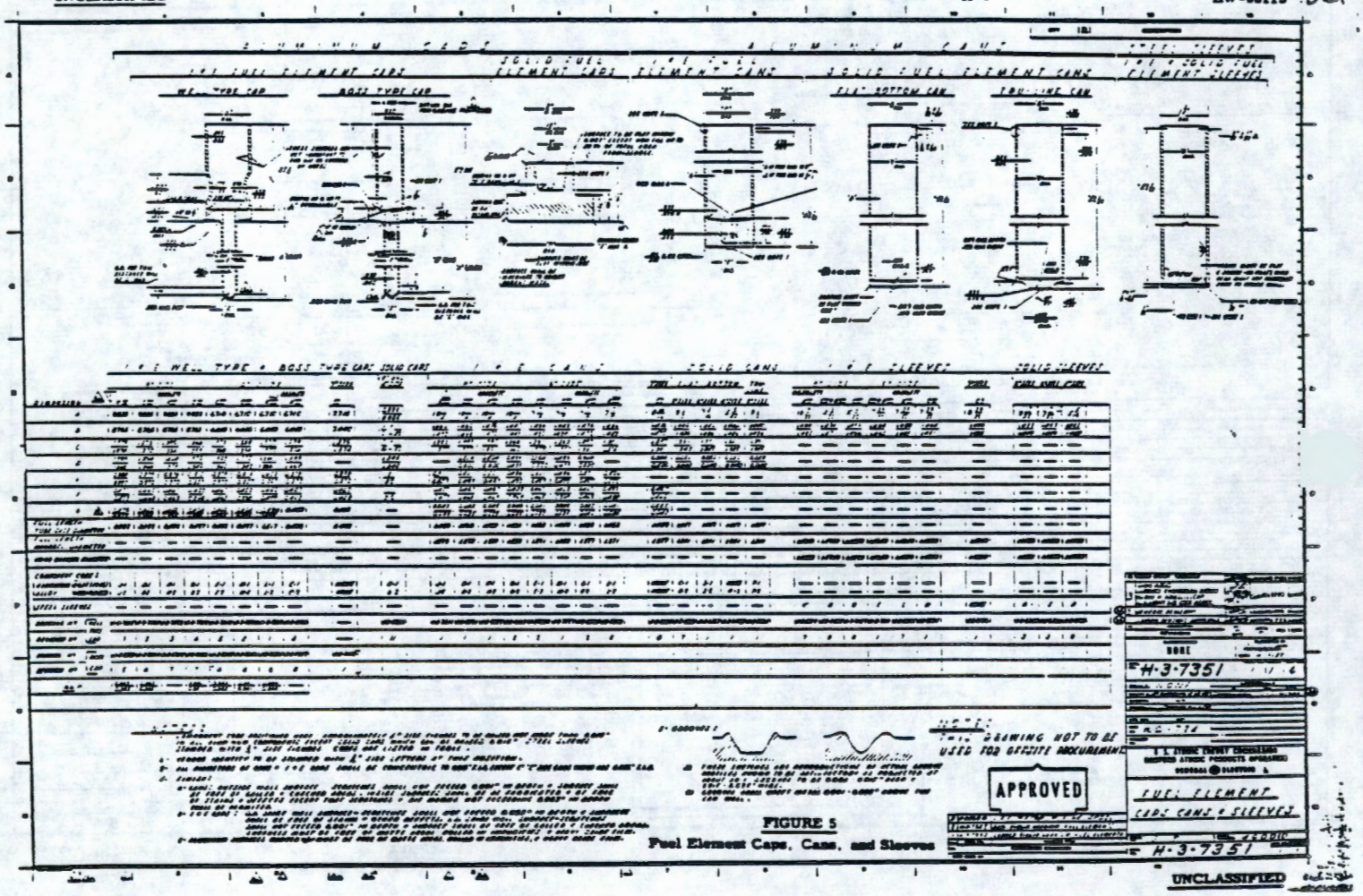


FIGURE 5

Fuel Element Caps, Cans, and Sleeves

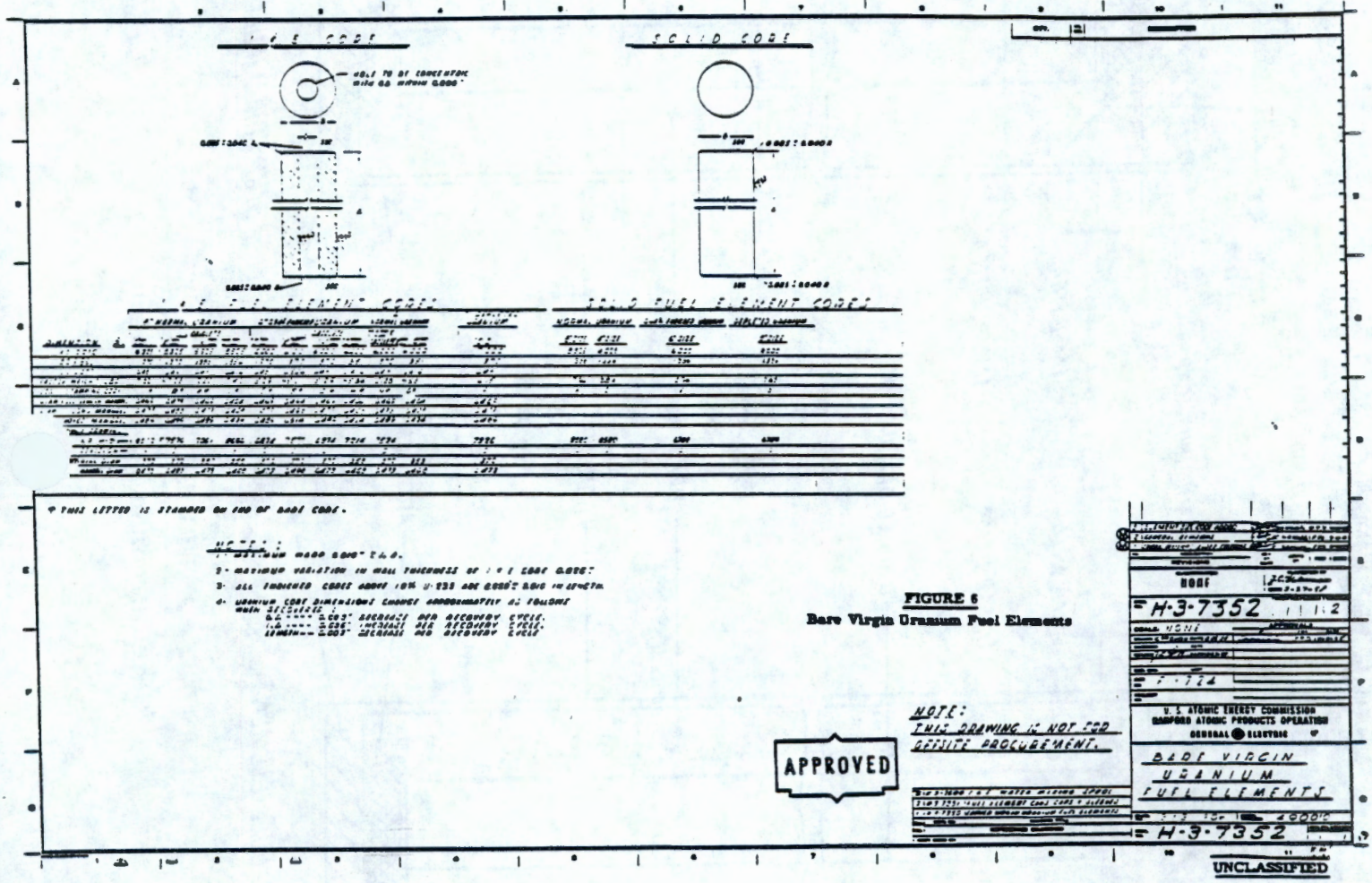


FIGURE 6
Bare Virgin Uranium Fuel Elements

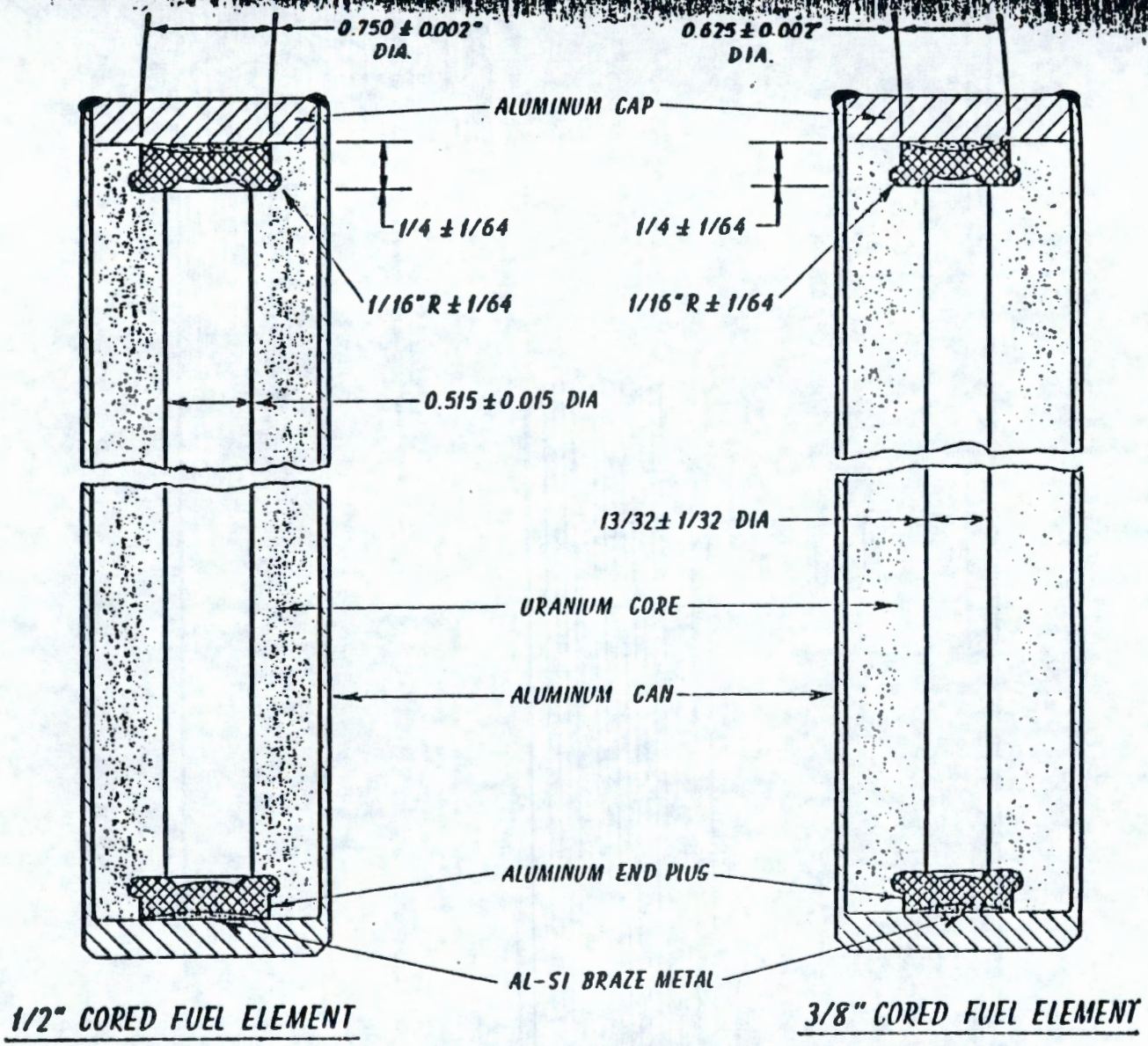


FIGURE 7

Cored Uranium Fuel Elements

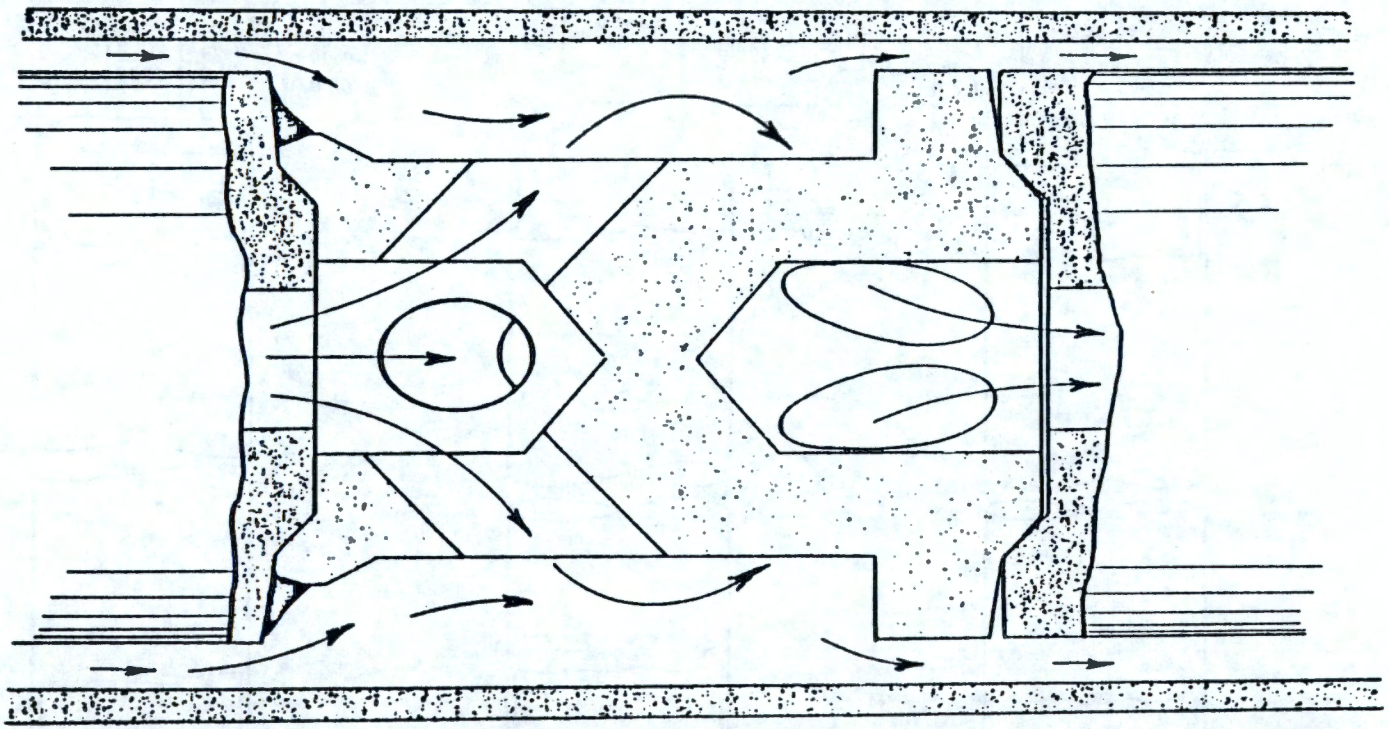


FIGURE 8

I & E Water Mix Piece

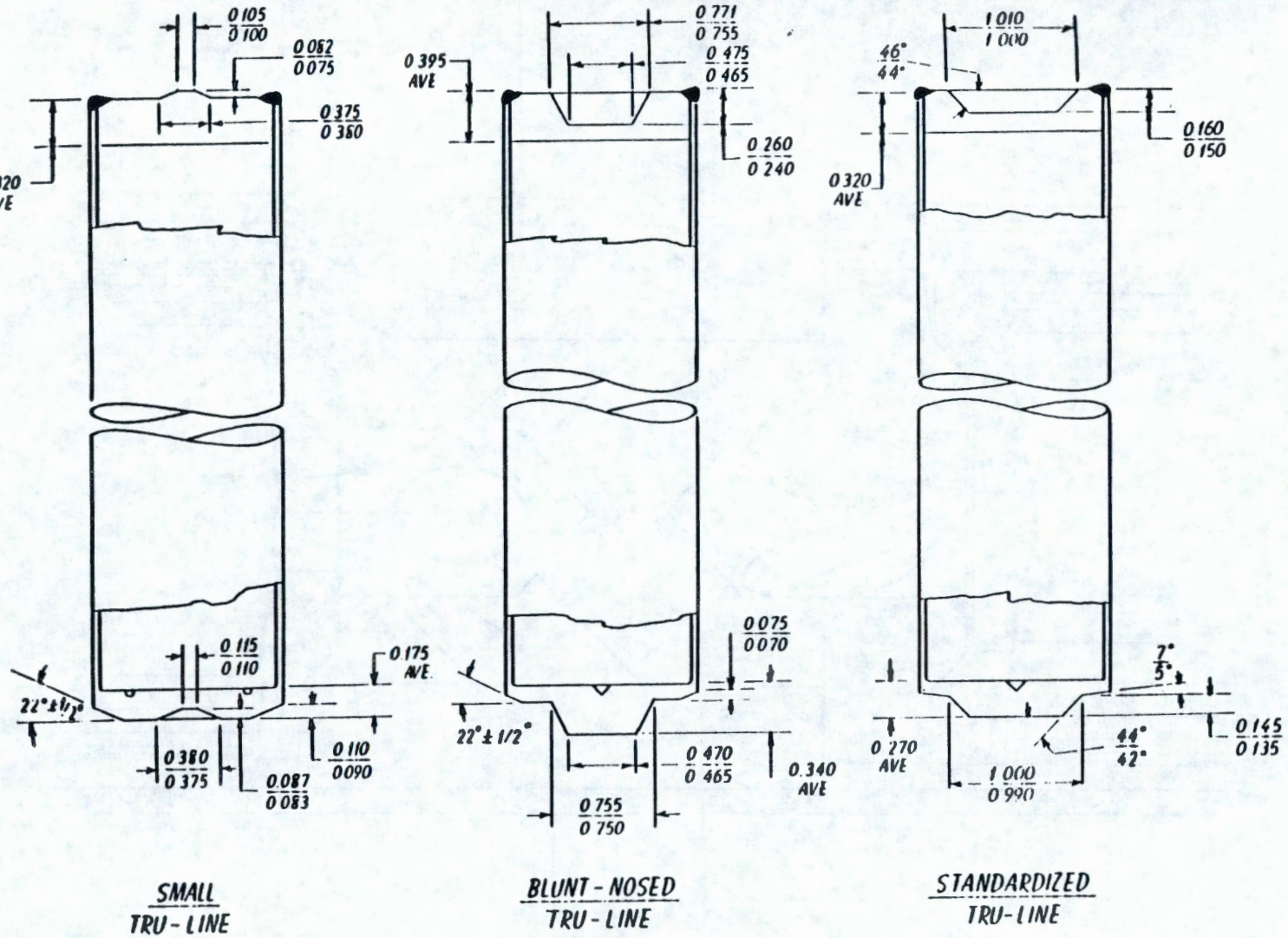


FIGURE 9

Solid Fuel Element Tru-Line Features

AEC-GE RICHLAND, WASH.

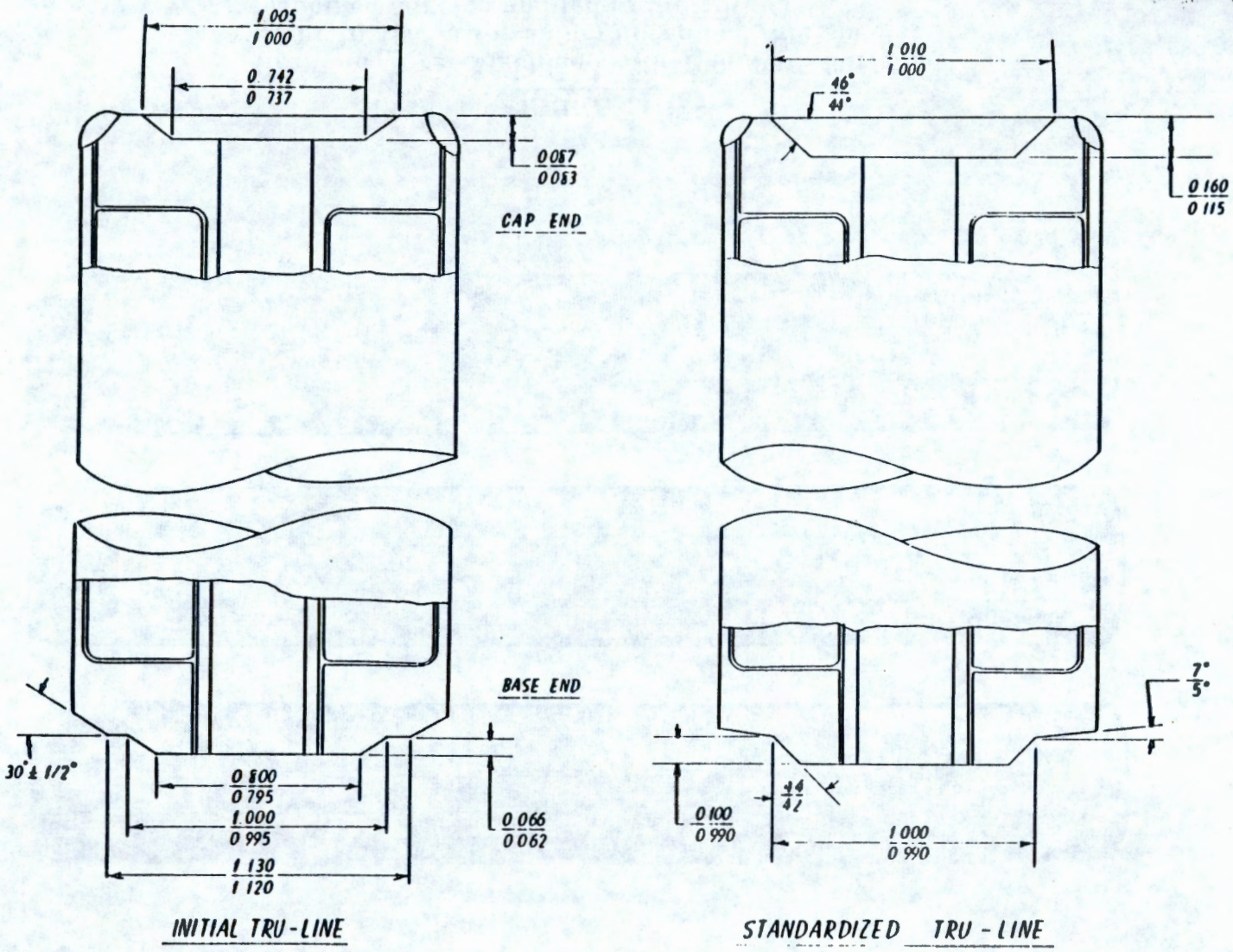


FIGURE 10

I & E Fuel Element Tru-Line Features

ARP-66 RICHLAND, WASH.

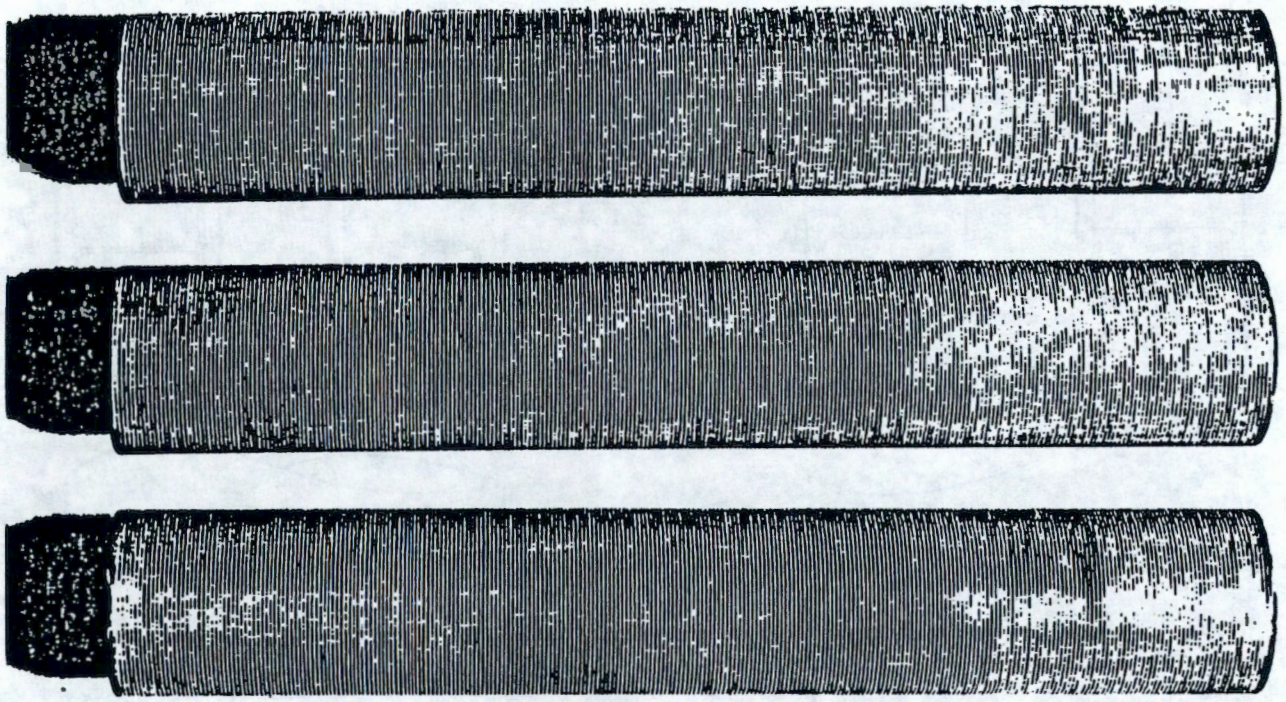


FIGURE 11

Uranium Cores Machined with 1000 RMS Surface Prior to 1953 all uranium cores had this special machined surface applied to the core O. D.

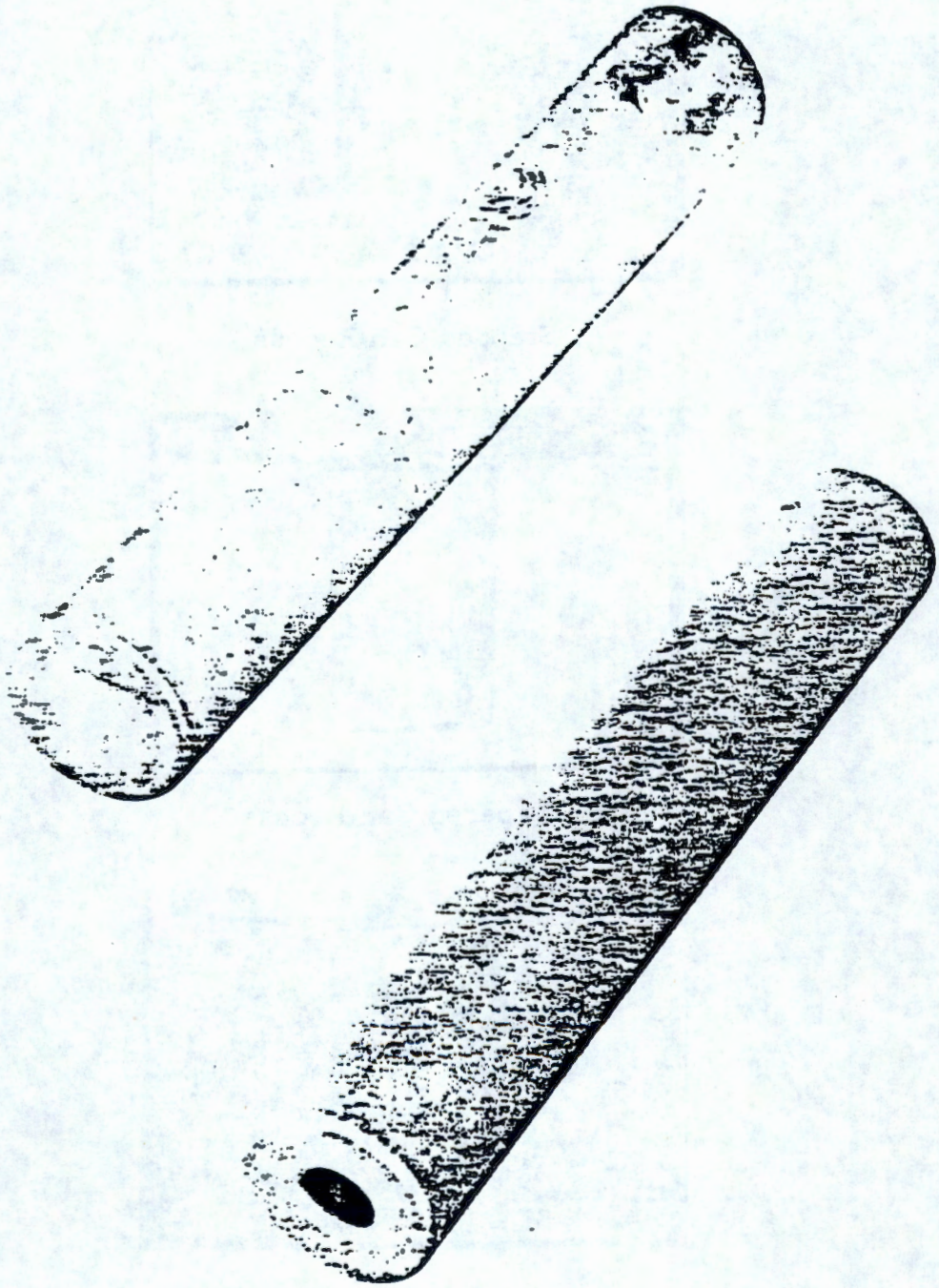
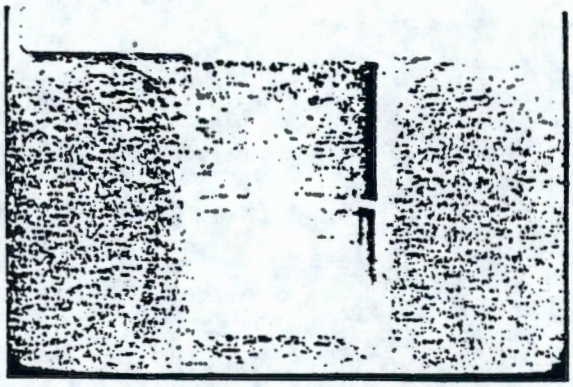


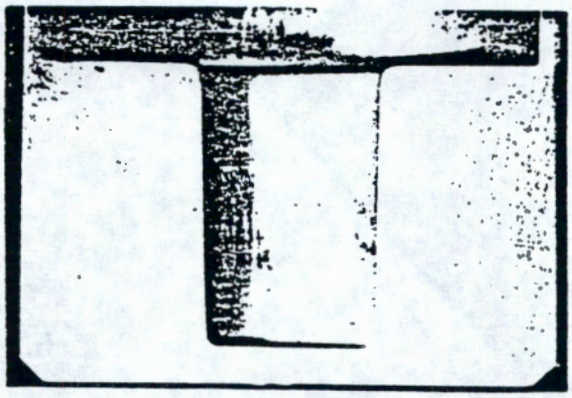
FIGURE 12

Present As-Machined Uranium Core Surface

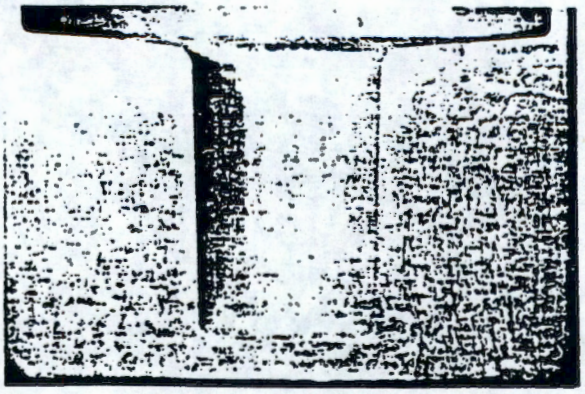
AEC-GE RICHLAND, WASH.



A. Stepped Can Recess



B. Tapered Can Recess



C. Tapered Can Recess with 5° Base Taper

FIGURE 13

Sections of Aluminum Can Bases Used for I & E Fuel Elements

ASE-GE RICHLAND, WASH.

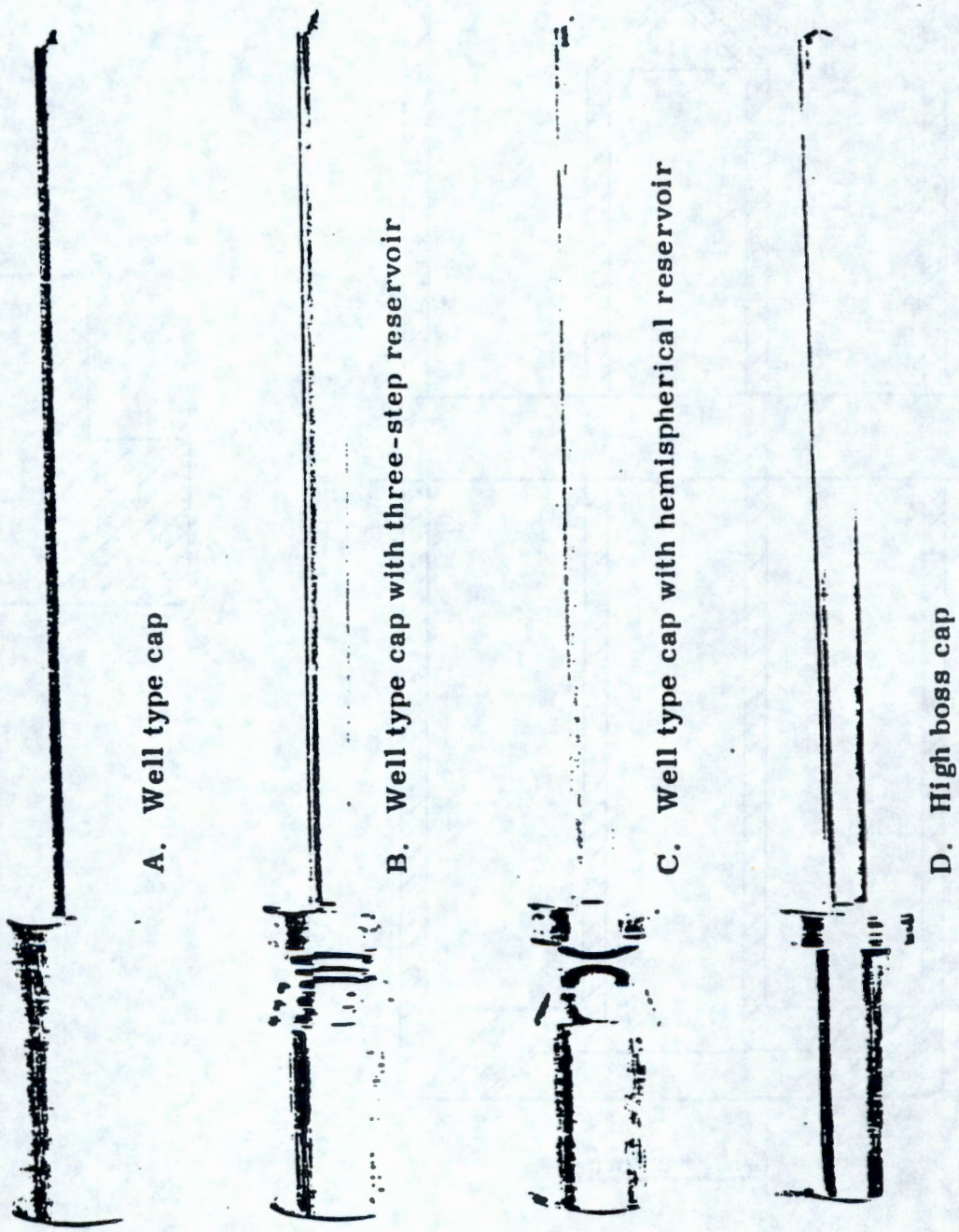
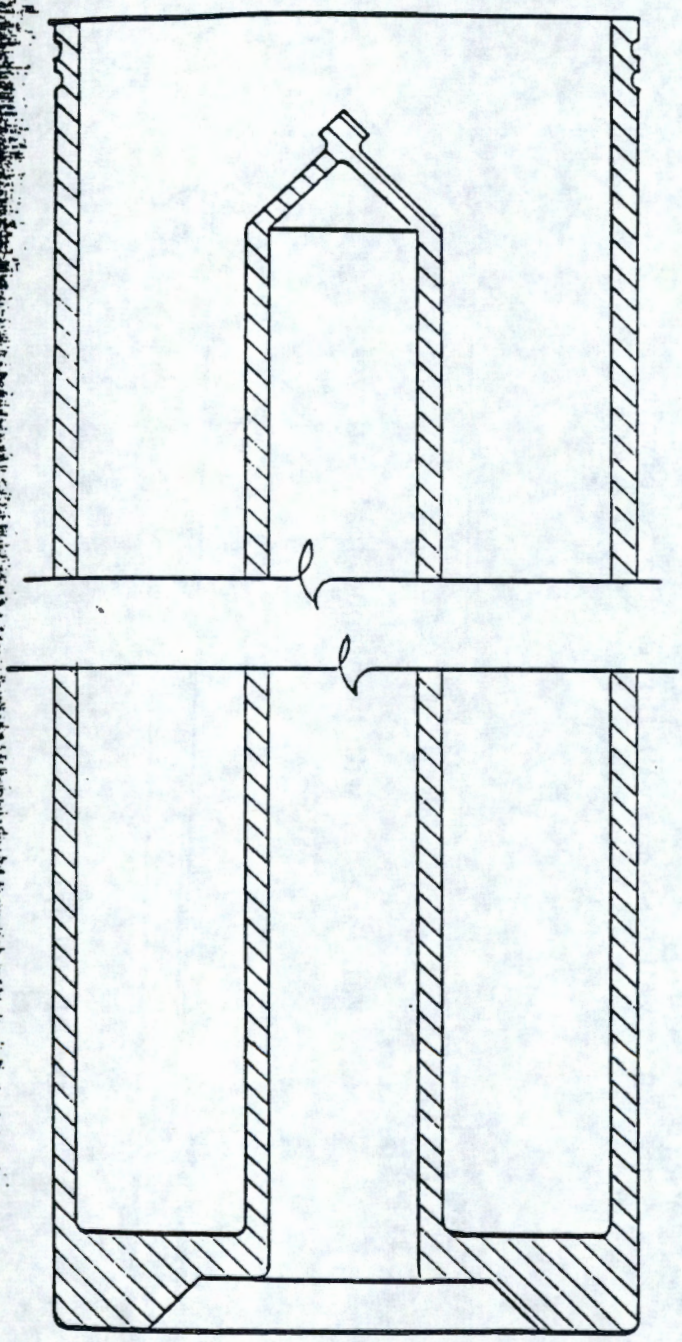


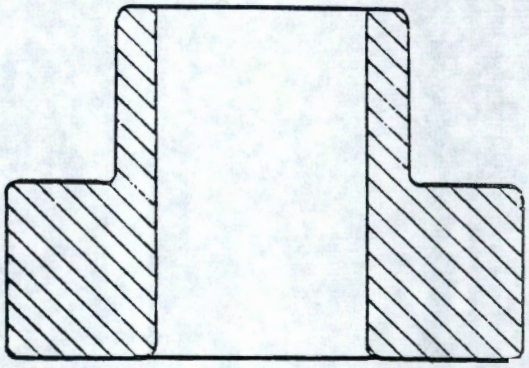
FIGURE 14

Aluminum Cap-Spires Used for I & E Fuel Elements

AEC-GE RICHLAND, WASH.



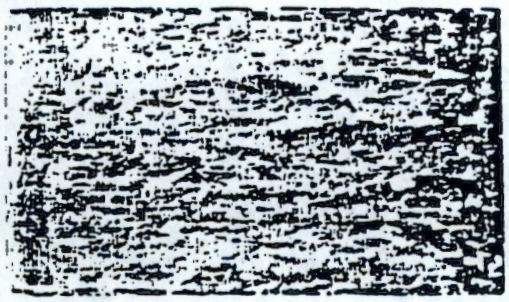
CAN - SPIRE



CAP

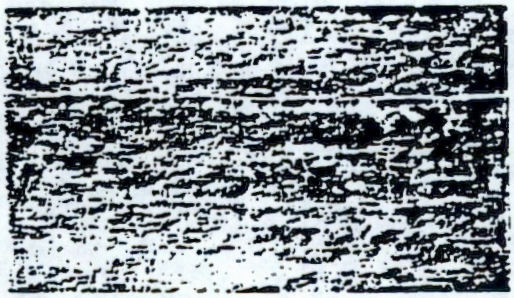
FIGURE 15

Aluminum Components for Can-Spire Canning

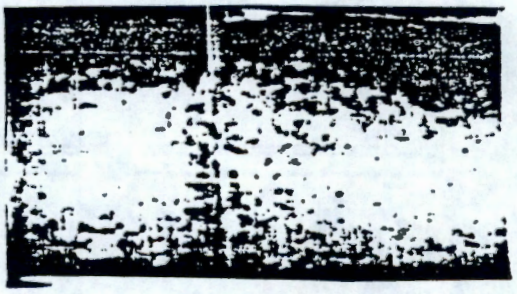


Current

Total
Hydrogen
Content 2.2 ppm



Vacuum
Outgassed



Total
Hydrogen
Content 0.5 ppm

Dingot
High Purity
Uranium

Total
Hydrogen
Content 4.0 ppm

FIGURE 16

Examples of Braze Layer Porosity

The examples on the right are autoradiograph films of canned fuel elements. The examples on the left are the mechanically removed can walls from the same fuel elements on the right.

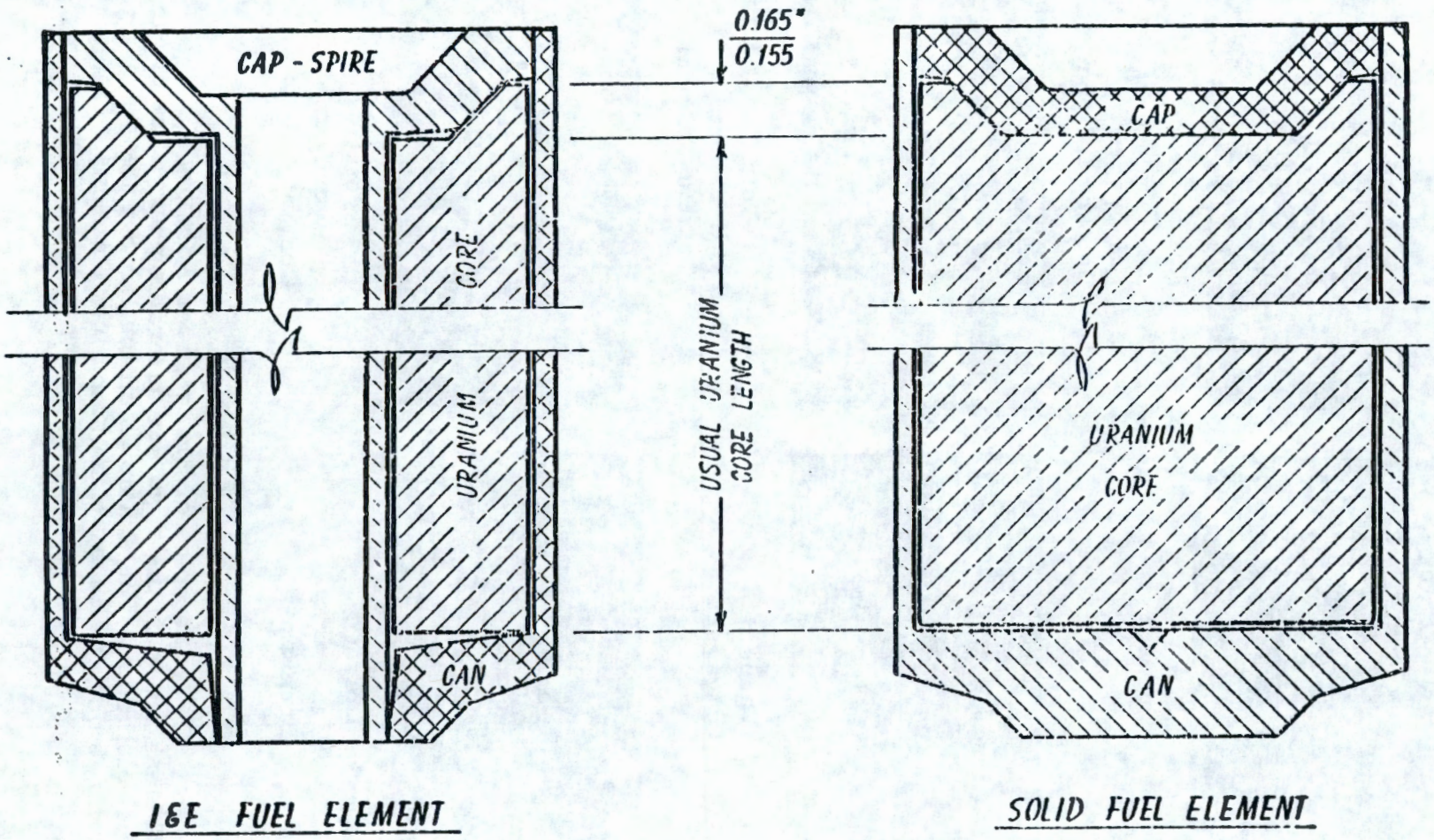


FIGURE 17

Tru-Line Uranium Core Fuel Element

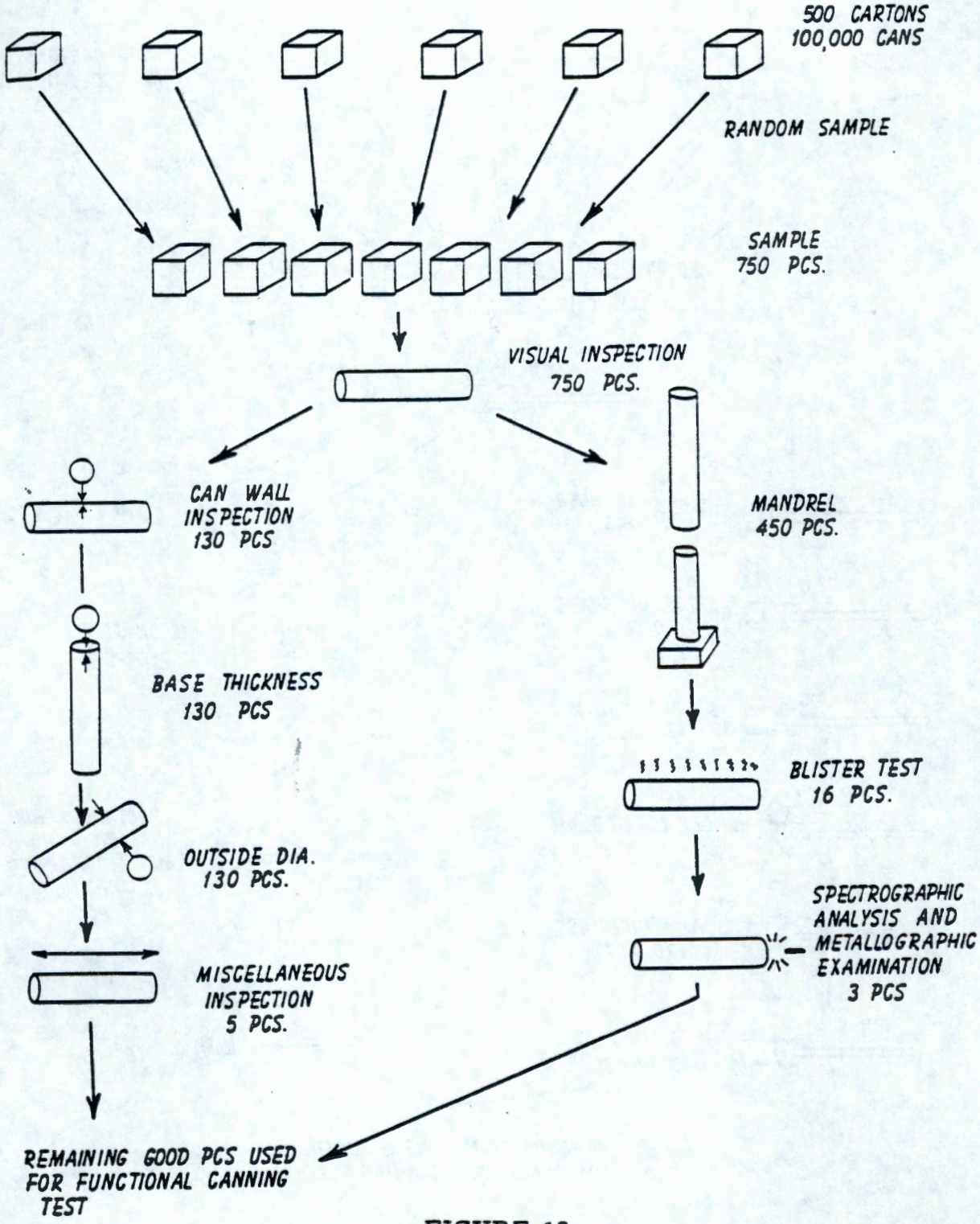


FIGURE 18

Example of Acceptance Sampling - Aluminum Cans

ADC-GE RICHLAND, WASH.

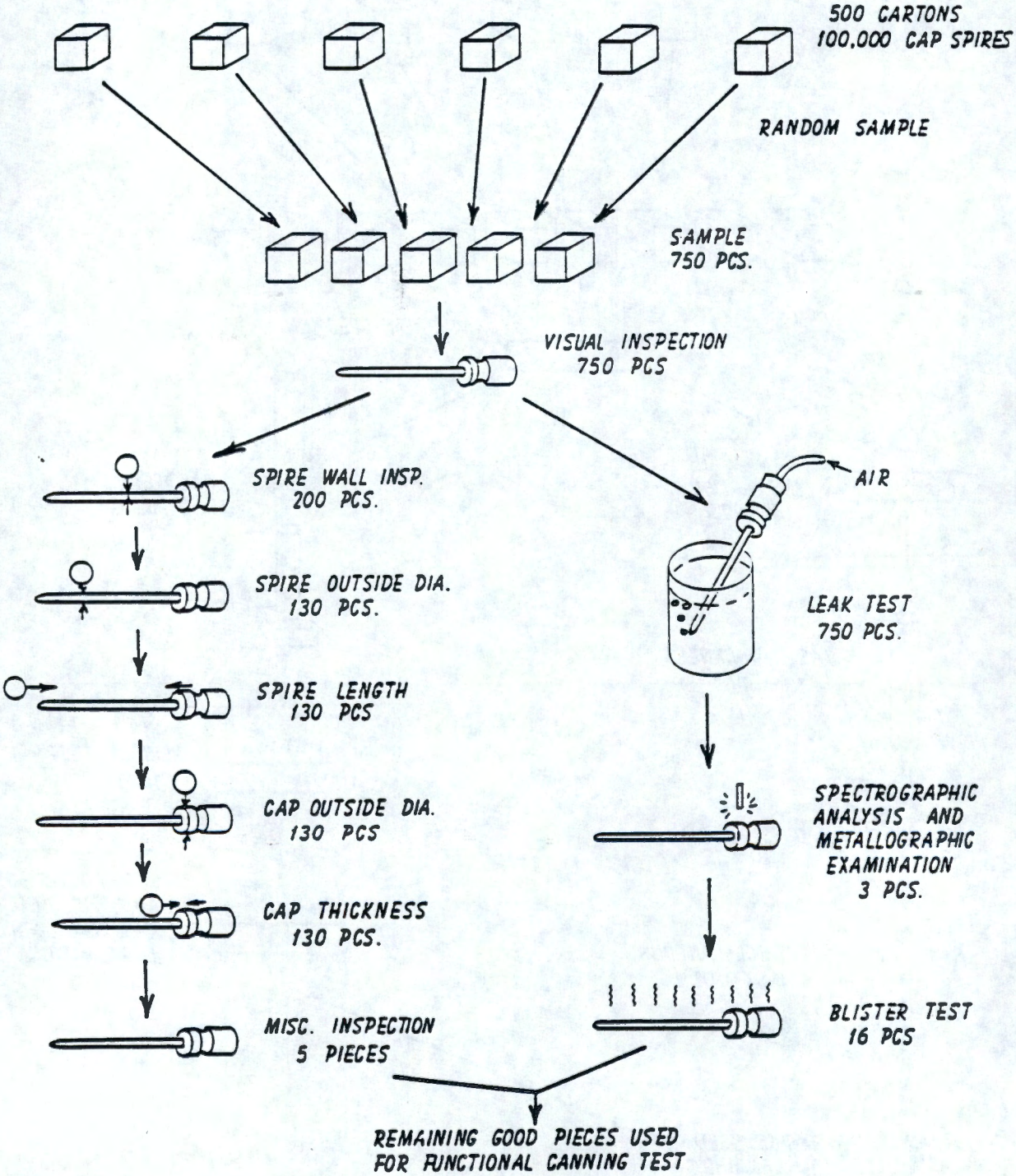


FIGURE 19

Example of Acceptance Sampling - Aluminum Cap-Spires

ARC-GE RICHLAND, WASH.

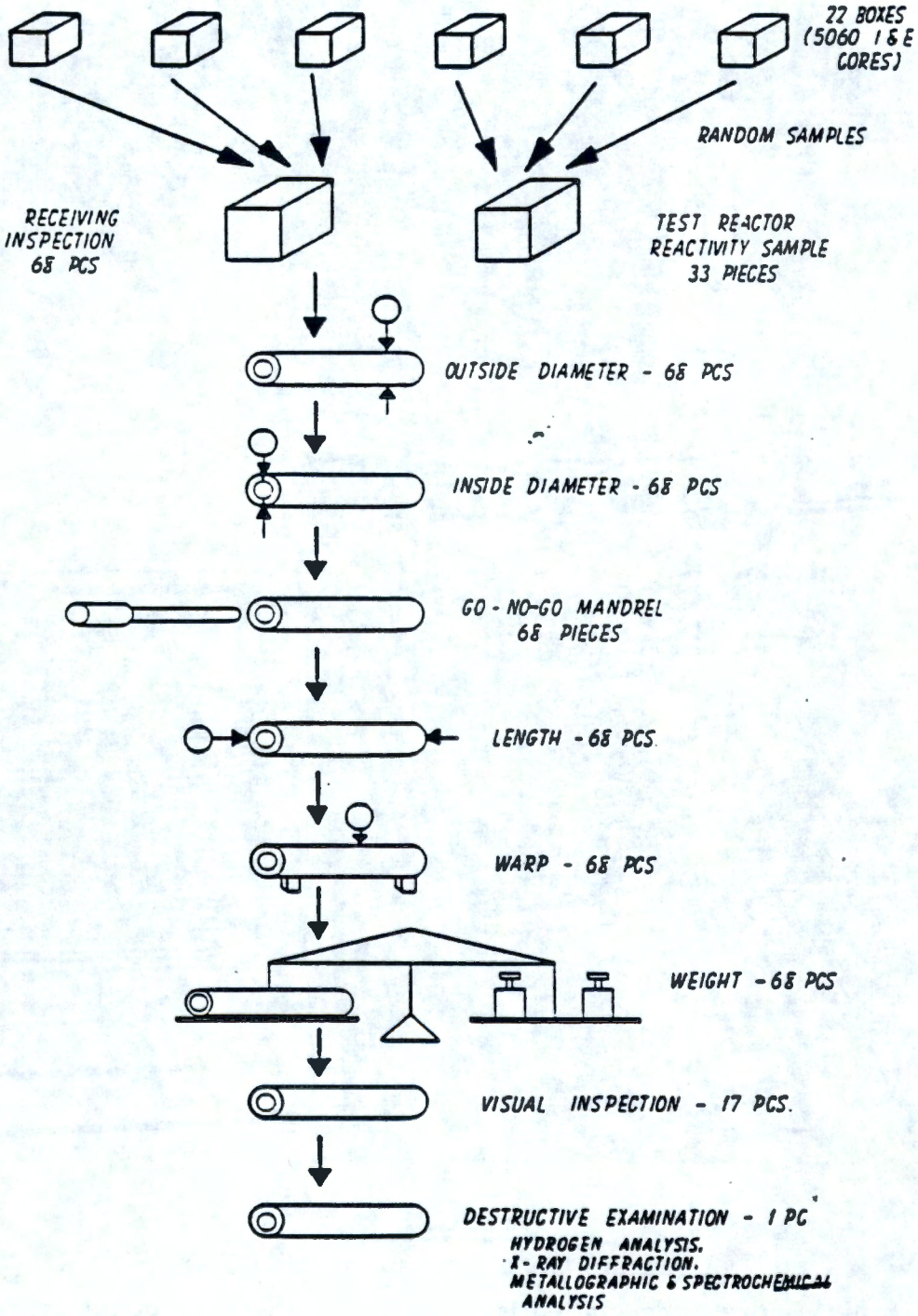


FIGURE 20

Example of Acceptance Sampling - Natural Uranium Cores

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WITH DELETIONS

[redacted]

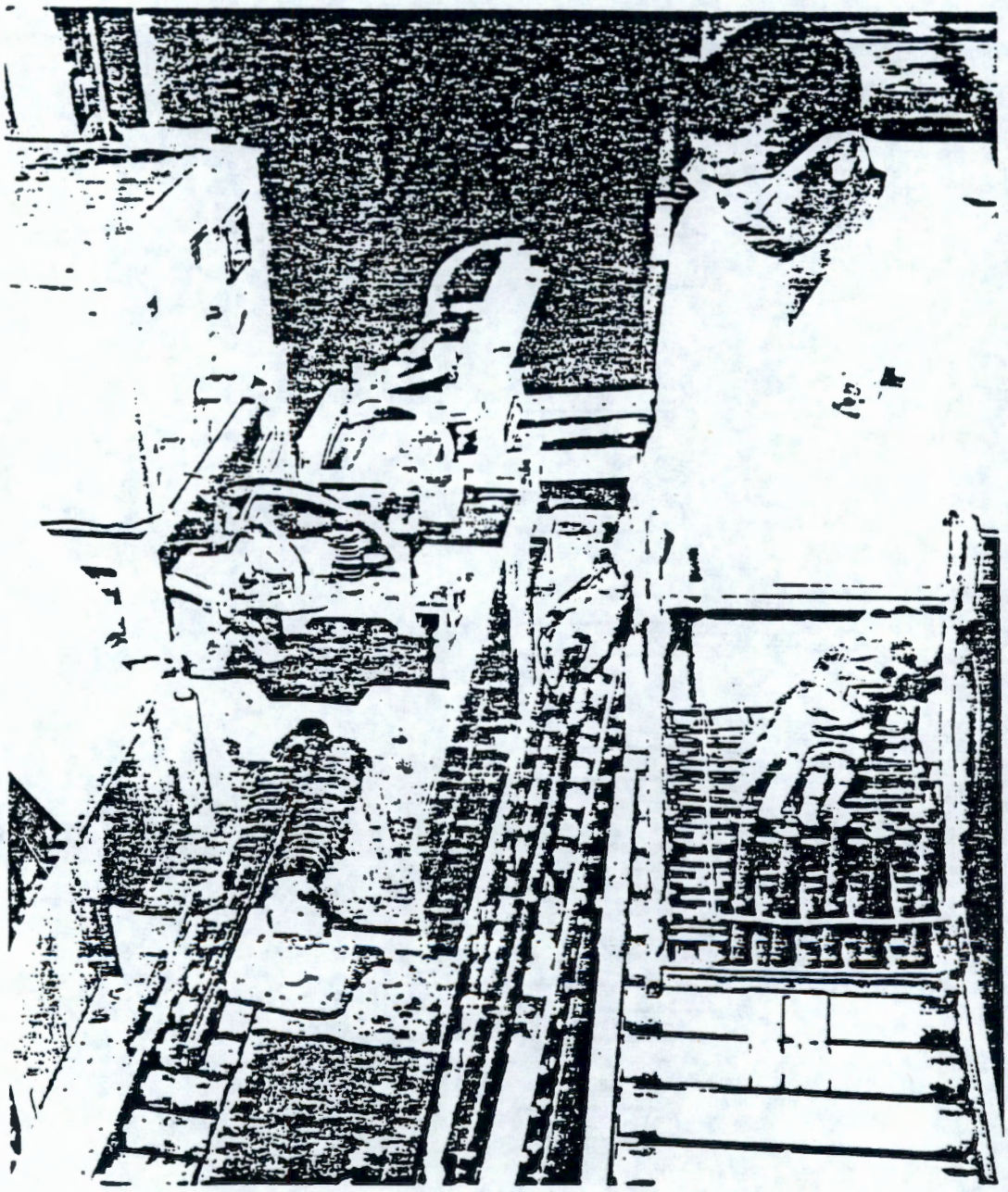

FIGURE 21

Uranium Core Transformation Tester

Uranium cores are loaded in the chute at the rear of the tester and the cores automatically pass through the tester to the unload station where the operator removes them and places them in the etch baskets. Two testers are in use.

[redacted]

AEC-GE RICHLAND, WASH.

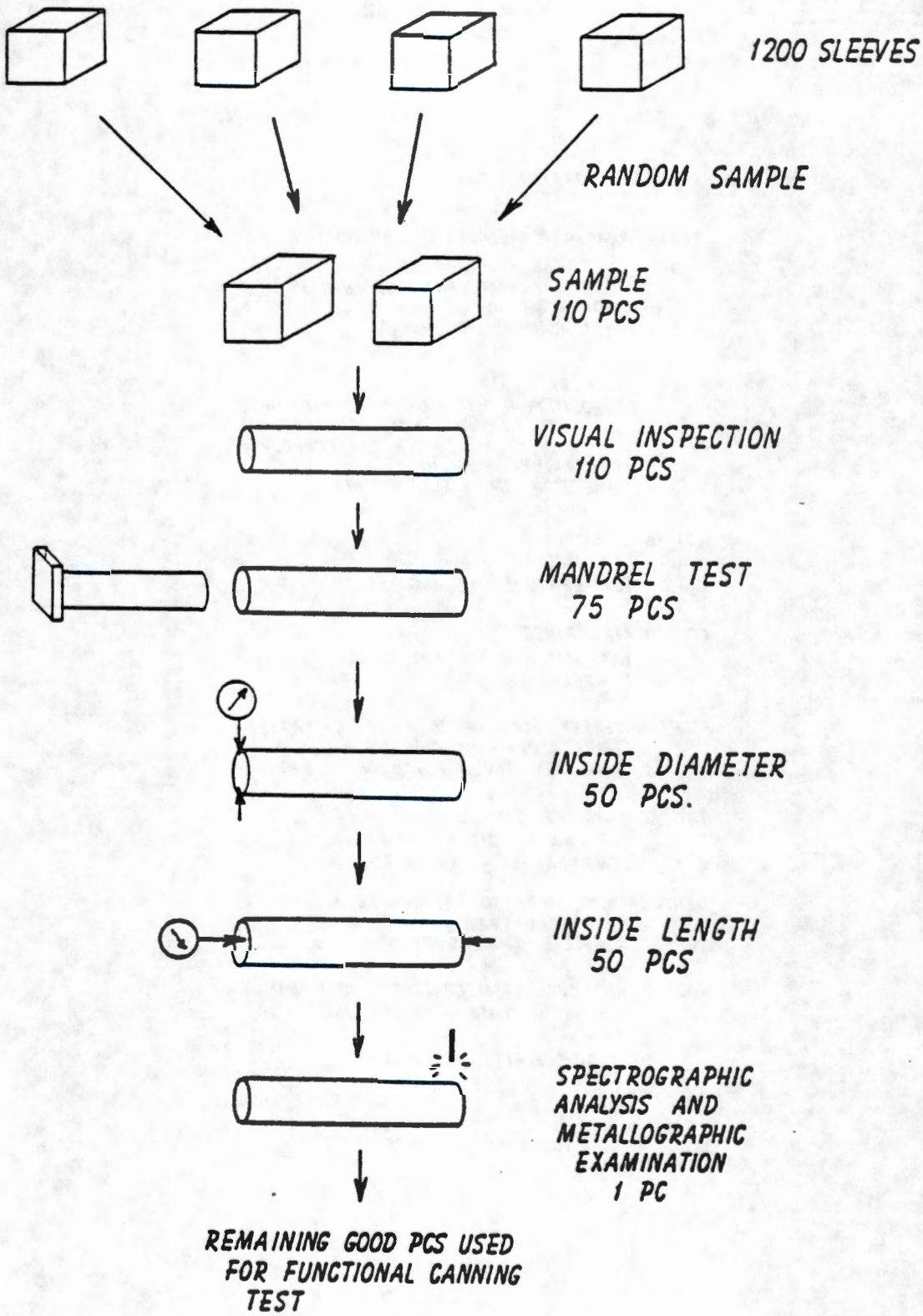

FIGURE 22

Example of Acceptance Sampling - Steel Sleeves

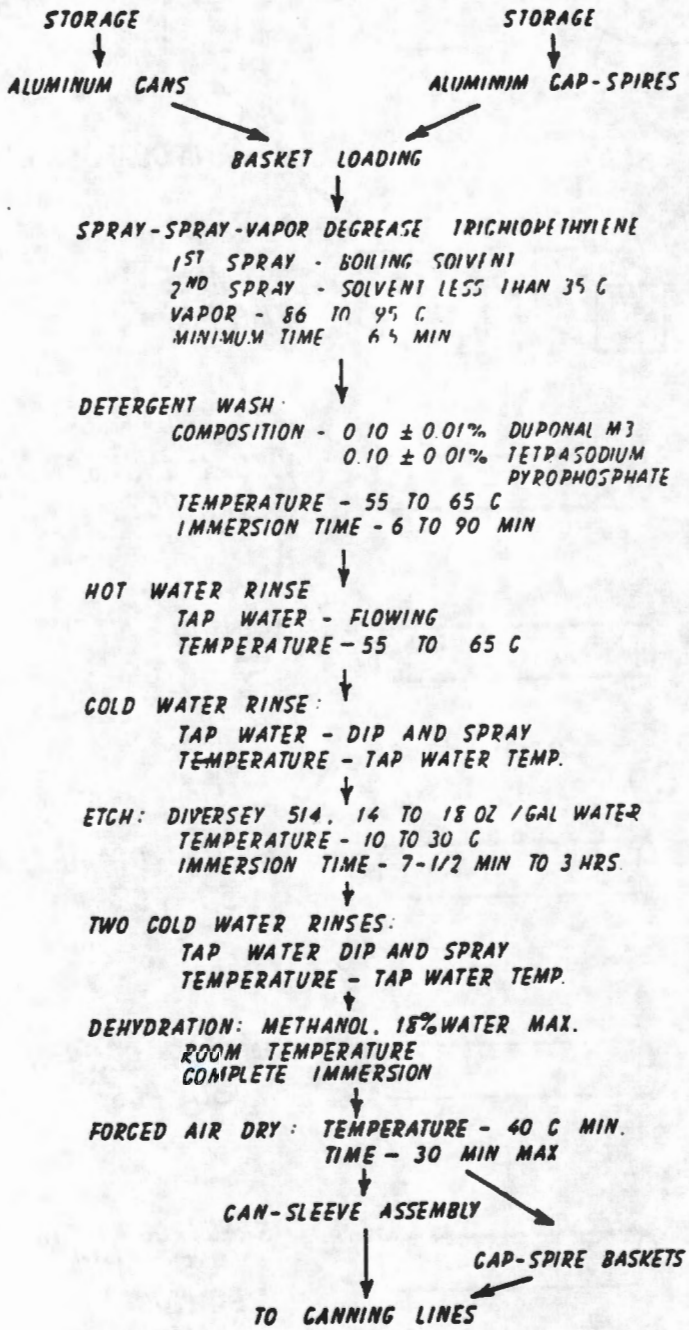

FIGURE 23

Aluminum Component Preparation Flowsheet

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WITH DELETIONS

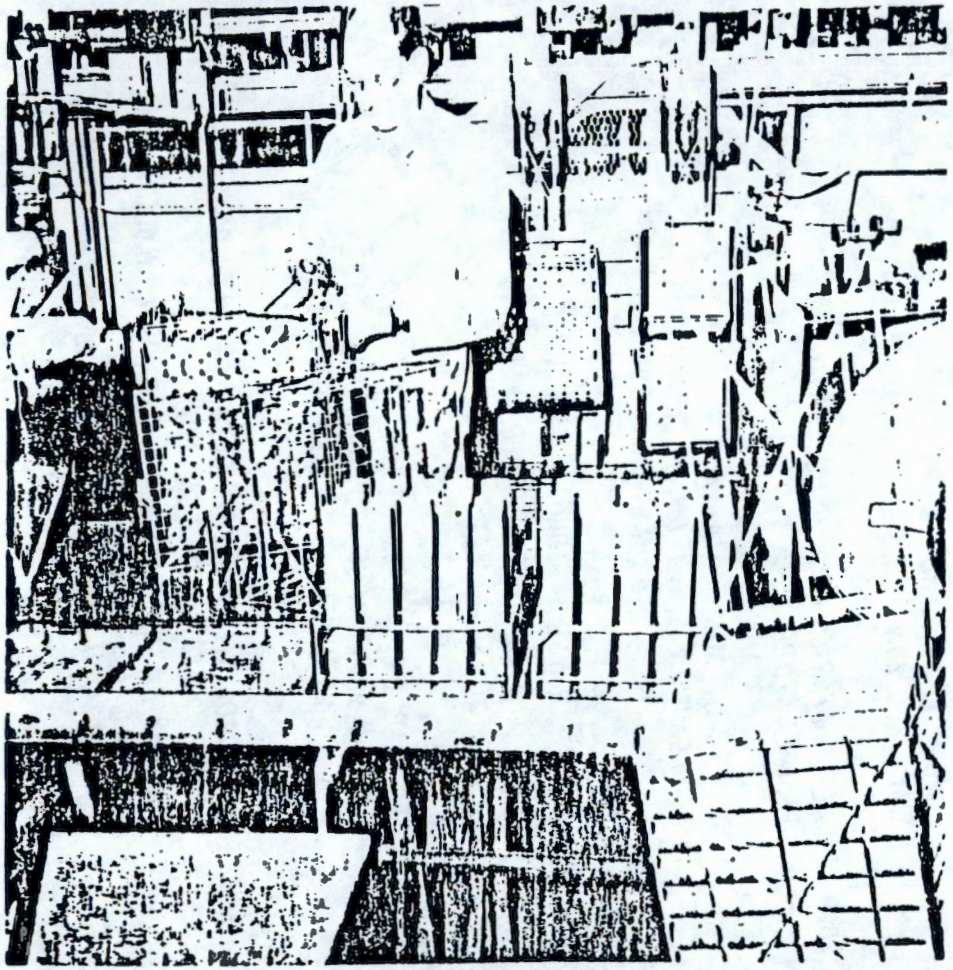

FIGURE 24

Cap and Can Cleaning Machine Load-Unload Station
Dirty caps and cans are loaded into baskets (middle) and placed on cleaning racks (background). The component baskets pass automatically through the cleaning machine and are removed at this station. The clean cans are assembled into the clean steel sleeves (foreground) and conveyed to the brazing lines. A second cleaning machine is on a standby basis.

ACC-AE RICHLAND, WASH.

STORAGE

↓

TRANSFORMATION TEST

↓

BASKET LOADING

↓

VAPOR DEGREASE: TRICHLORETHYLENE
VAPOR TEMP: 86 TO 95 C
TIME - 1 MIN, 55 SEC MINIMUM

↓

DIP PICKLE: NITRIC ACID 45% MINIMUM
TEMPERATURE: 55 TO 65 C
TIME: 2 MIN. 15 SEC MIN.
4 MIN. MAXIMUM
CONTAMINANTS: IRON - 0.25% MAX
URANIUM: 6% MAX

↓

COLD WATER RINSE - FLOWING TAP WATER
ELAPSED TIME BETWEEN PICKLE AND RINSE - 20 SEC. MAX.

↓

FORCED AIR DRY: TEMP. - 50 TO 75C
TIME - SUFFICIENT TO DRY THE CORE WITHOUT EXCESSIVE OXIDATION

↓

BASKET UNLOADING & PICKLED CORE INSPECTION
CORES ARE INSPECTED FOR:
1. OXIDATION - MAX., LIGHT BROWN IN COLOR
2. METAL QUALITY DEFECTS
3. COMPOUND LAYER REMAINING IF RECOVERED CORES

↓

CONVEYOR BASKET LOADING

↓

TO CANNING LINES

FIGURE 25

Uranium Core Preparation Flowsheet

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WITH DELETIONS

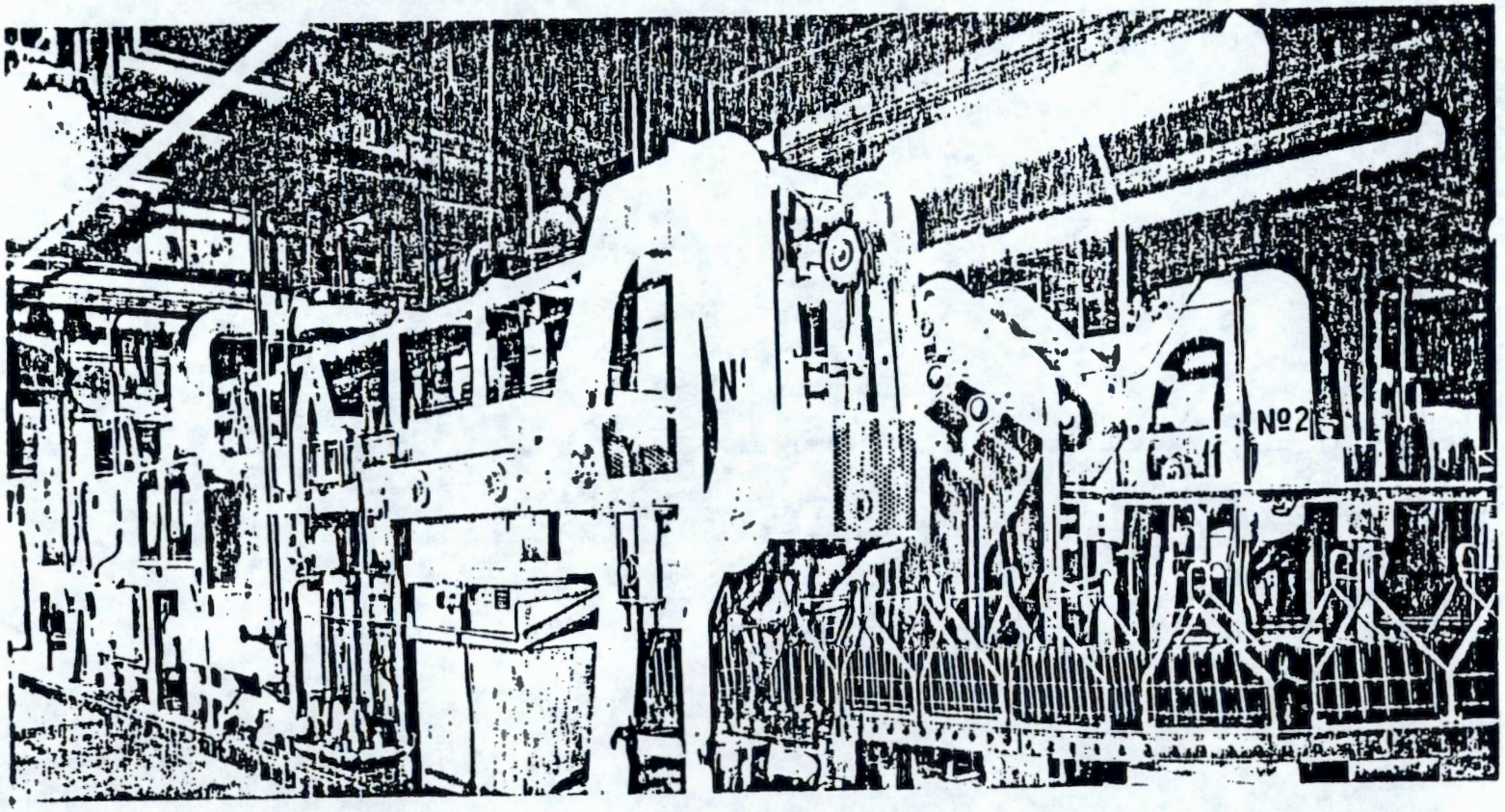

FIGURE 26

Uranium Core Etch Machine

Baskets of uranium cores are automatically conveyed through the etch machine to the etch inspection station at the far end. The second etch machine can be seen in the background.

ASF-46 RICHLAND, WASH.

NEW SLEEVE STORAGE

↓

DEGREASE: TRICHLORETHYLENE
VAPOR TEMP: 86 TO 95 C
1. SLEEVES ARE FILLED AND EMPTIED SEVERAL TIMES IN THE BOILING SOLVENT AND IN THE CLEAN CONDENSATE
2. VAPOR DEGREASED

↓

FIRST SOAP WASH: IVORY SOAP, ONE OZ / GAL
TEMP - 45 TO 60 C
INSIDE OF SLEEVE IS BRUSHED TO REMOVE ANY PARTICLES

↓

SECOND SOAP RINSE: IVORY SOAP, ONE OZ / GAL

↓

HOT AIR DRY

↓

STORAGE → CAUSTIC CLEANING

USED SLEEVES FROM QUENCH TANK → CAUSTIC CLEANING

CAUSTIC CLEANING: NaOH - 22 TO 30%
TEMP - 85 TO 95 C
TIME - 90 SECONDS MINIMUM
CONTAMINATION - 0.8% ALUMINUM, MAX
MAX. SOLUTION LIFE - 100 OPERATING LINE-SHIFTS

↓

HOT SPRAY RINSE: HOT TAP WATER
TEMP - 50 C MINIMUM
SPRAY PRESS - 20 PSIG MIN

↓

SOAP DIP: IVORY SOAP, 0.2 TO 1.0%
TEMP - 50 TO 70 C
MAX. SOLUTION LIFE - ONE DAY

↓

DIP-SPRAY RINSE: TAP WATER

↓

COATING DIP: SODIUM ALUMINATE, 0.4 TO 0.6%
TEMP - 70 TO 90 C
MAX. SOLUTION LIFE - ONE DAY

↓

HOT AIR DRY: OPTIMUM TEMP. 65 C

↓

CONVEYOR BASKET LOADING

↓

CAN-SLEEVE ASSEMBLY

↓

TO CANNING LINES

FIGURE 27

Steel Sleeve Preparation Flowsheet

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WITH DELETIONS

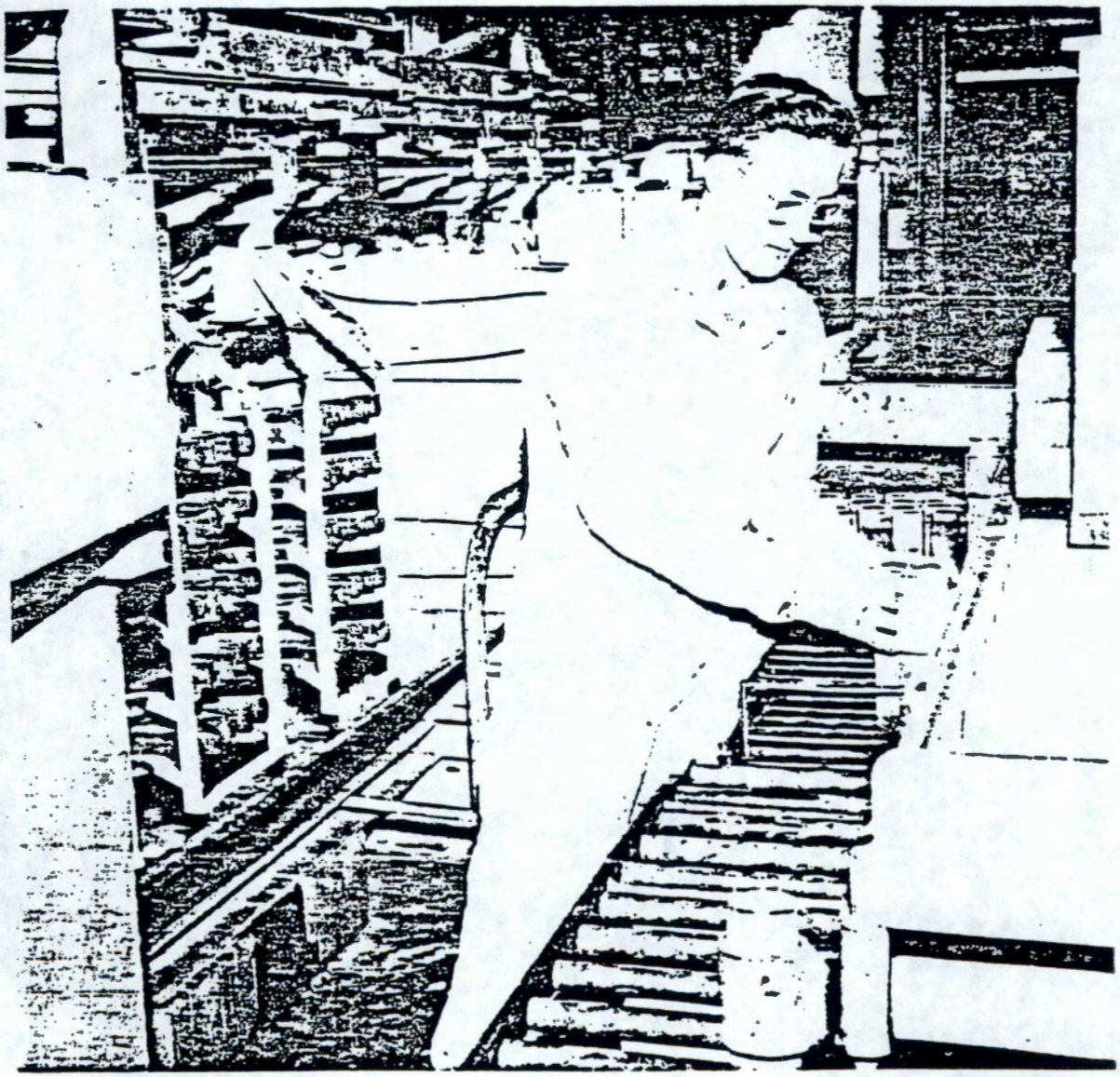

FIGURE 28

Sleeve Cleaning Machine Load-Unload Station
Dirty sleeves are loaded on racks and passed automatically through the cleaning machine. The clean sleeves are also removed at this station, loaded into sleeve baskets (as shown) and sent to the brazing lines. A second cleaning machine is on a standby basis.

[redacted]

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[redacted]

FIGURE 29
Fuel Element Dip Brazing Flowsheet

[redacted]

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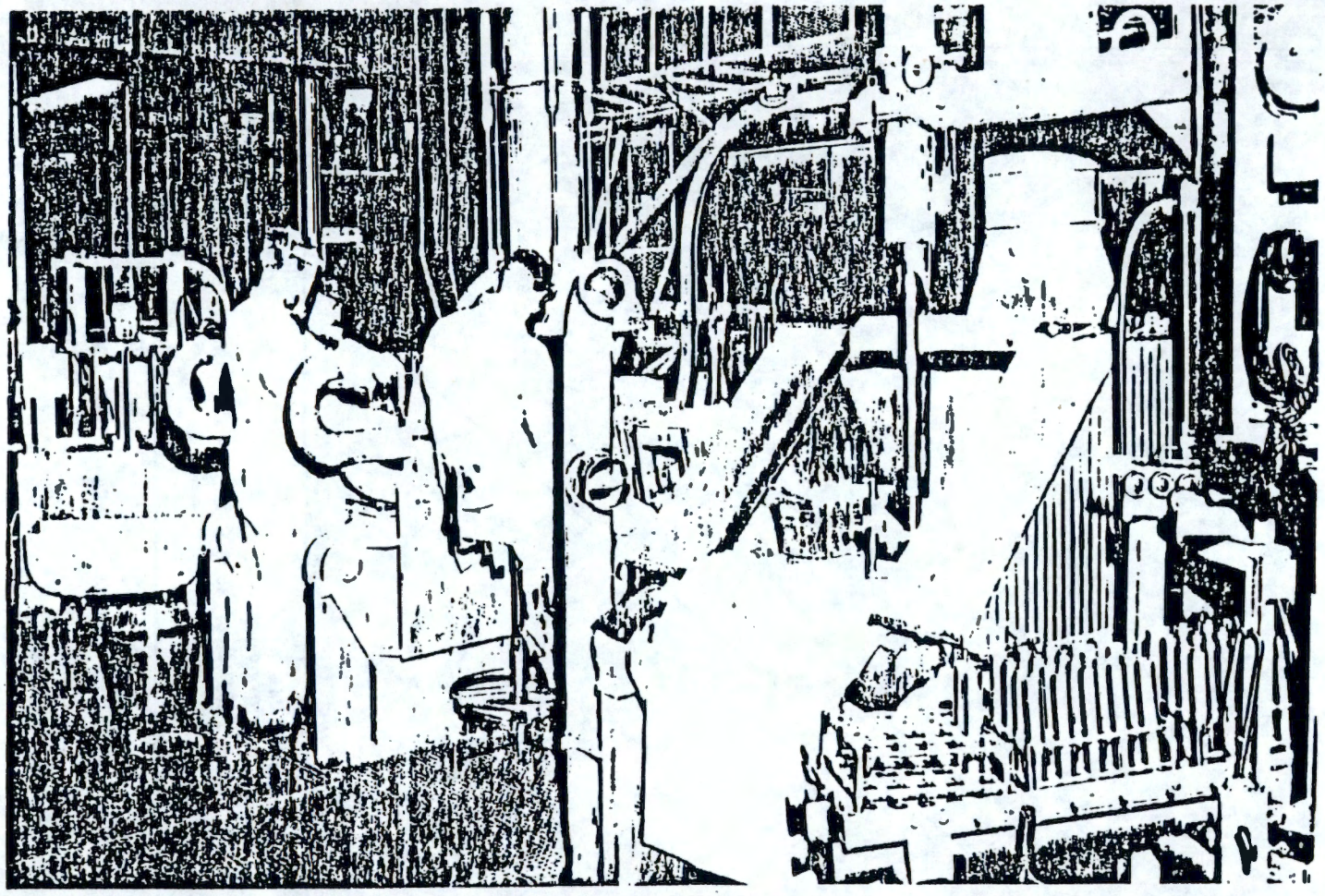

FIGURE 30

Brazing Furnace Area

The duplex furnace (foreground) preheats the uranium cores. The canning furnace (middle) is used for aluminum component preheating and fuel element assembling. Water quenching the assembled fuel elements in the quench tank (background) completes the brazing operation. There are six of these canning lines in the brazing area.

ARCAE RICHLAND, WASH.

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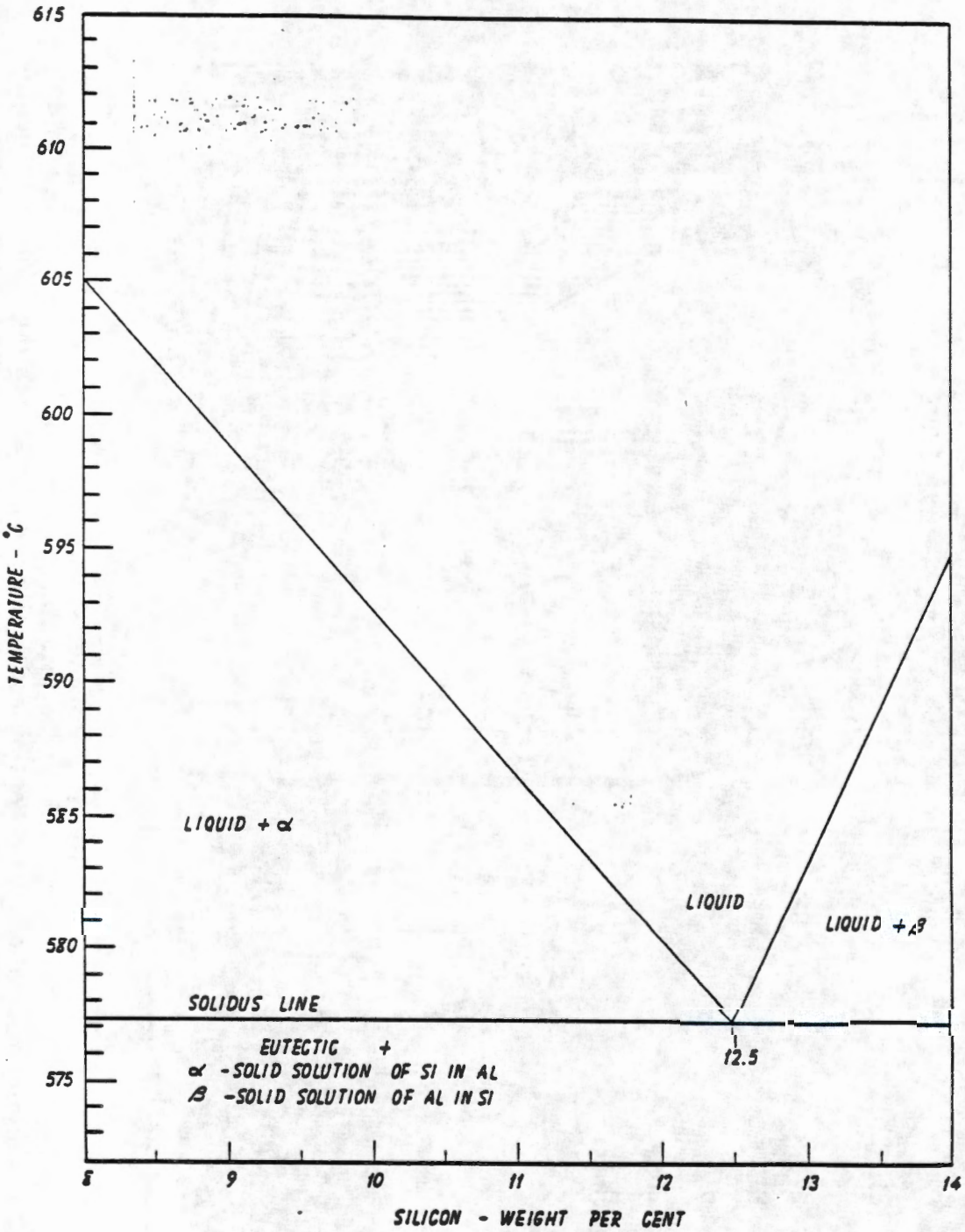


FIGURE 31

Al-Si Equilibrium Diagram

ABC-GE RICHLAND, WASH.

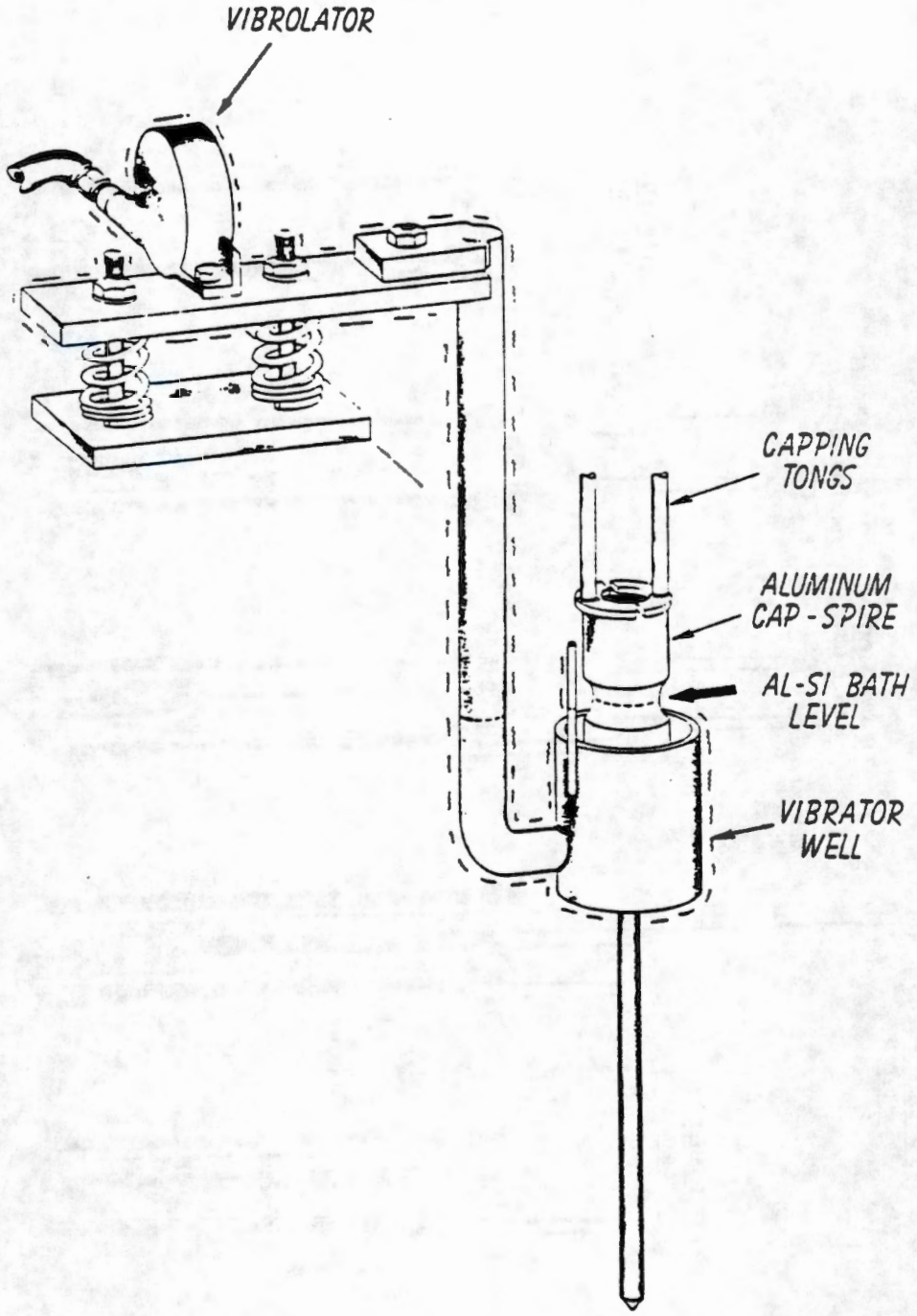


FIGURE 32

Cap-Spire Vibration Method

The vibrating well aids in cap wetting and removal of gas bubbles under the cap wafer. The vibration is produced by a Peterson "Vibrolator".

ASC-GE RICHLAND, WASH.

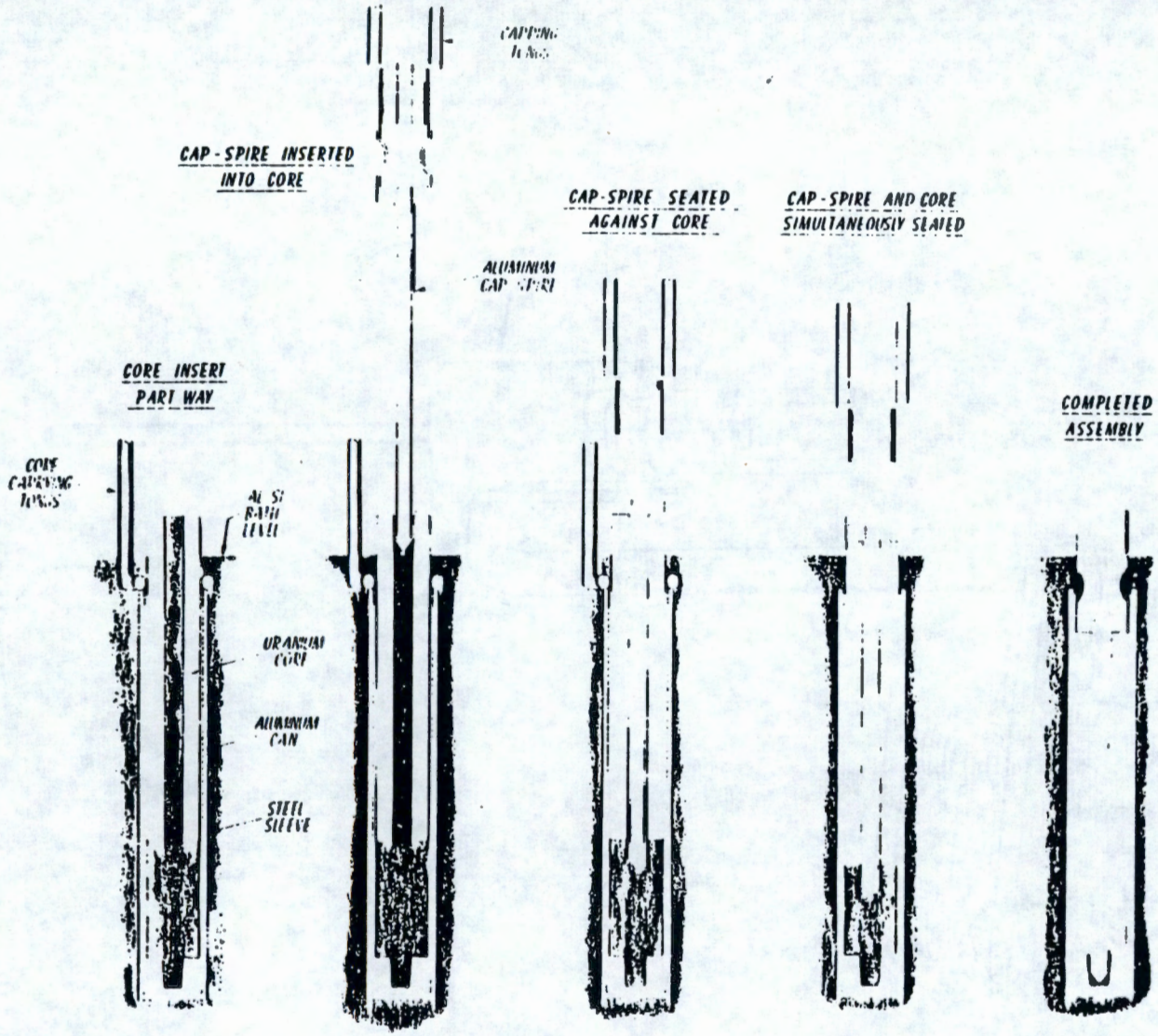


FIGURE 33

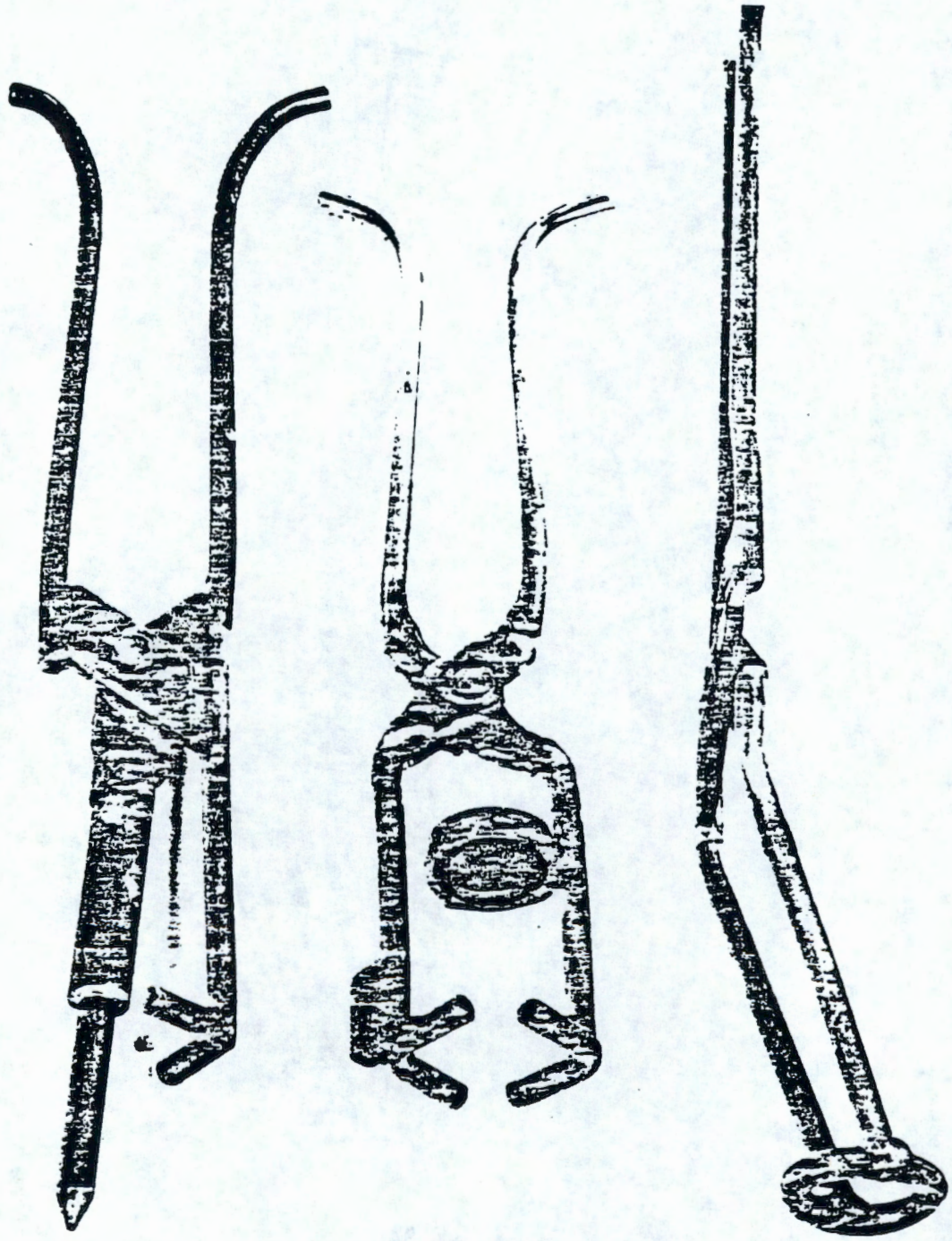
Spire-Core Canning Technique

FIGURE 34

Can-Sleeve Basket with Vibrator
and Sleeve Clamping Device

The can-sleeve assemblies are clamped into place during vibration. Vibration, with a Peterson "Vibrolator", aids in removal of entrapped air from the cans prior to fuel element assembly.

AEC-GE RICHLAND, WASH.



Core Prong Tong Splash Tong Spire-Core Tong

FIGURE 35

Uranium Core Carrying Tongs

AEC-GE RICHLAND, WASH.

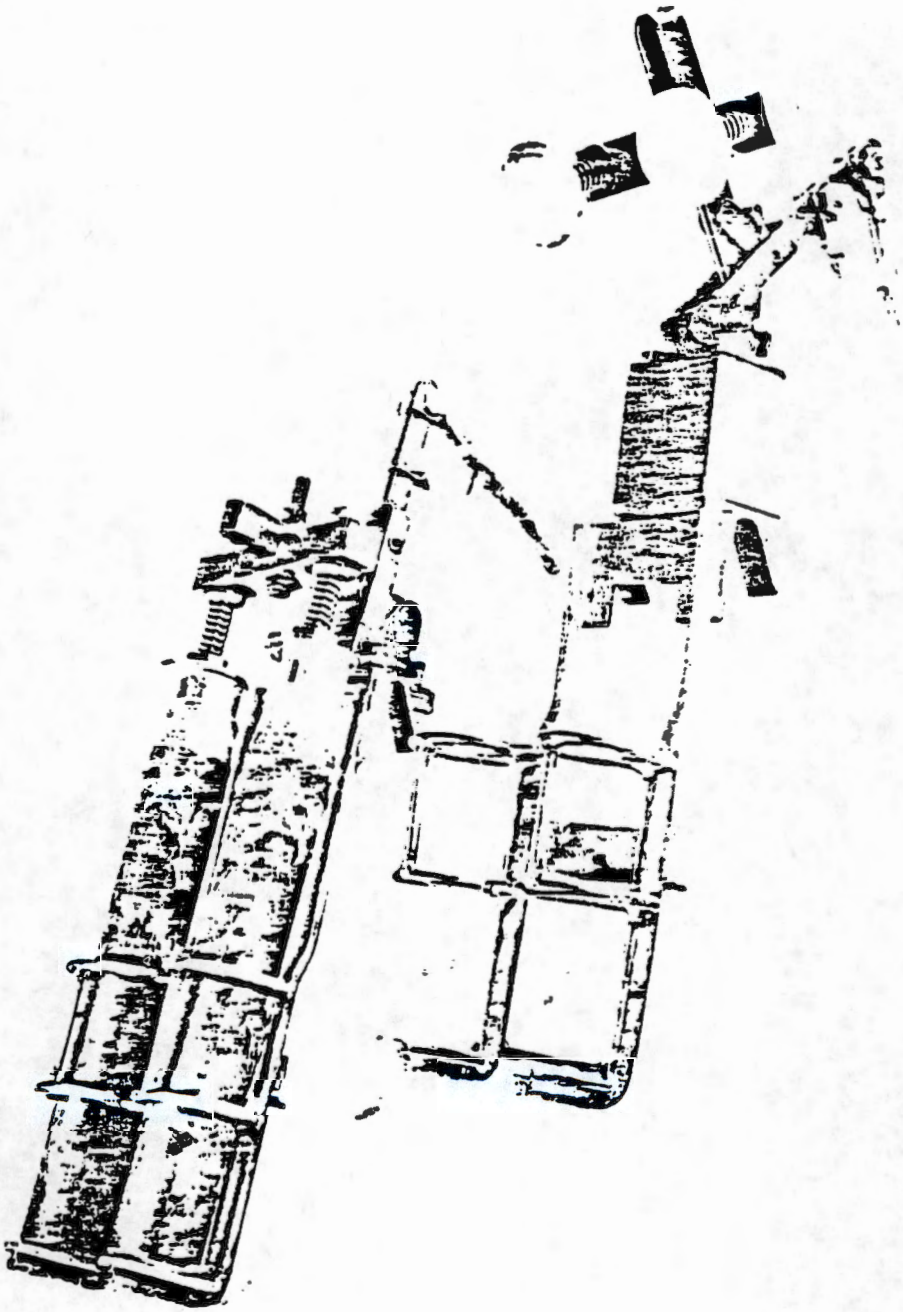


FIGURE 36

I & E Fuel Element Quench Basket
The cap hold-downs re-seats the cap-spires reducing high cap rejects.

ASC-GE RICHLAND, WASH.

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[redacted]

[redacted]

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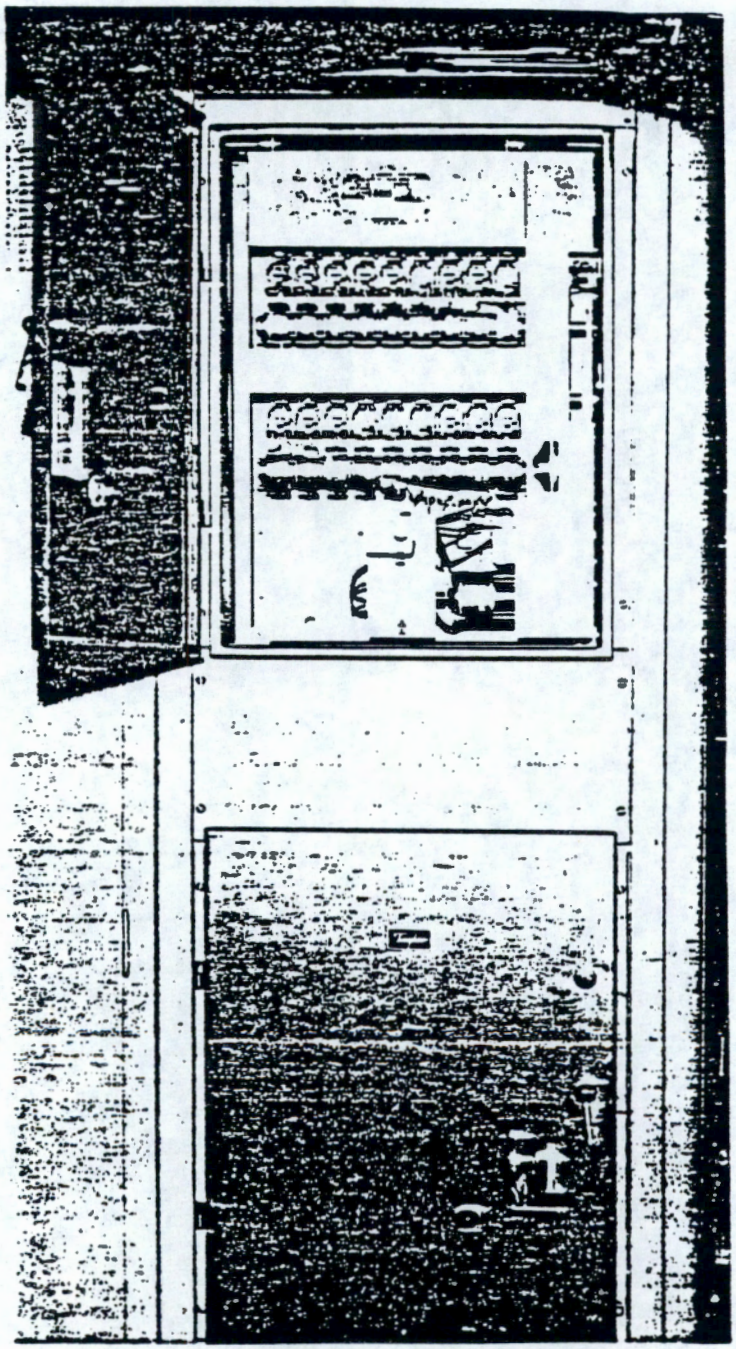
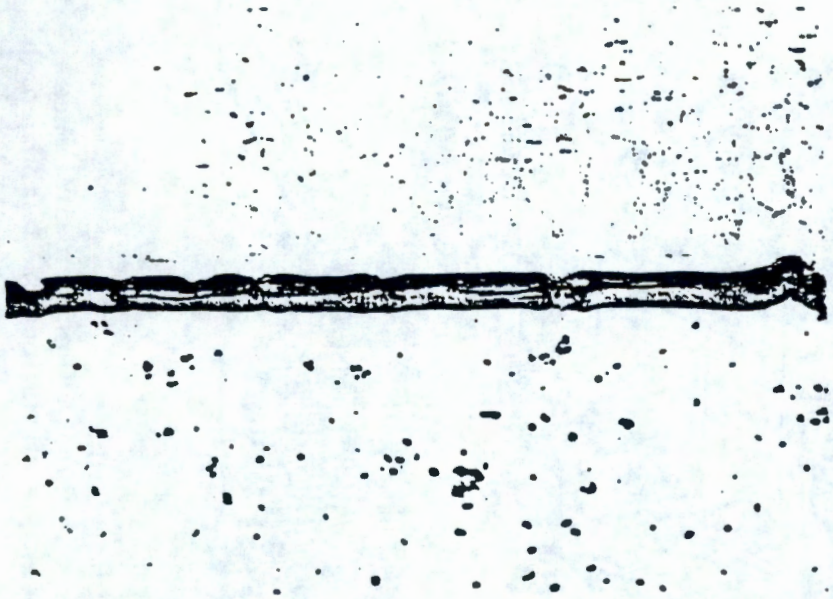


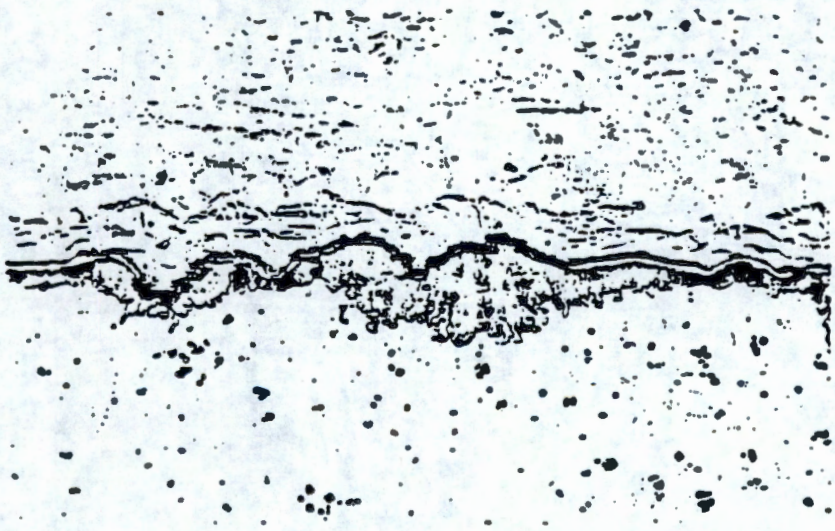
FIGURE 39

"Flex-O-Timer" for Controlling Brazing Cycles
This electro-pneumatic timing instrument controls the sequences of the brazing operation. Pins on rotating drums (shown in open instrument) actuate electrical switches which in turn operates the brazing equipment.

ABC-GE RICHLAND, WASH.



A. Typical Brittle Bond Layer 250X
Note the presence of cracks in the layer next to the uranium core.



B. Typical Tough Bond Layer 250X
Note the irregular boundary between the compound layers and the uranium and Al-Si.

FIGURE 40

Examples of Brittle and Tough U-Al-Si Bonding Layers

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FIGURE 41

Six Spindle Automatic Acme-Gridley Lathe

This particular lathe (one of four) is used for cap end machining. Other similar lathes are used for base end machining. On the right can be seen the statistical braze and length inspection station.

ARS-48 RICHLAND, WASH.

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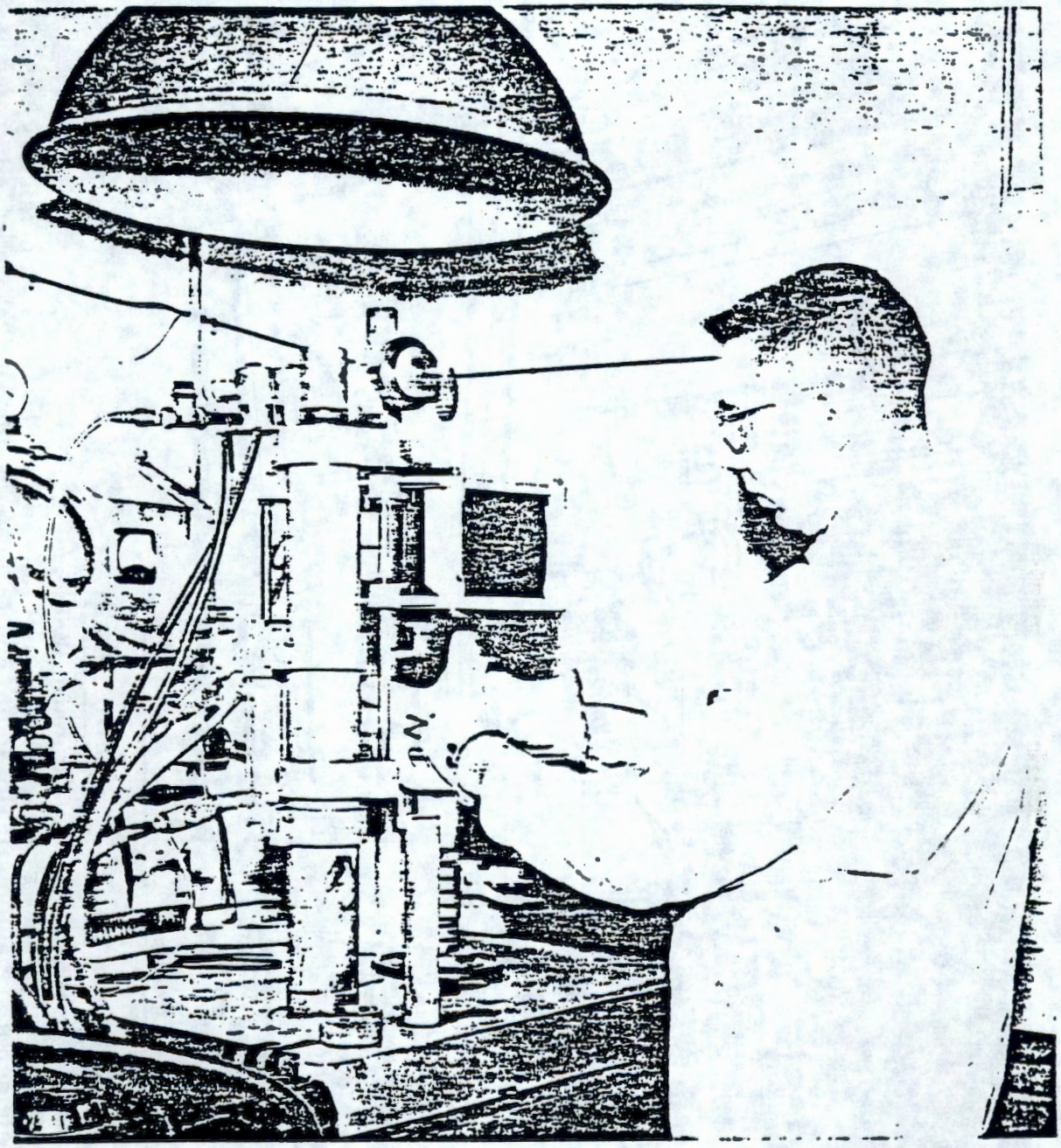

FIGURE 42

Semi-Automatic Welder

This welder is an inert-gas-shielded A.C. arc welder without filler metal additions. The welder automatically performs all of the crucial welding motions leaving the operator to load, unload, and push the start button. There are nine semi-automatic welders in use.

[redacted]

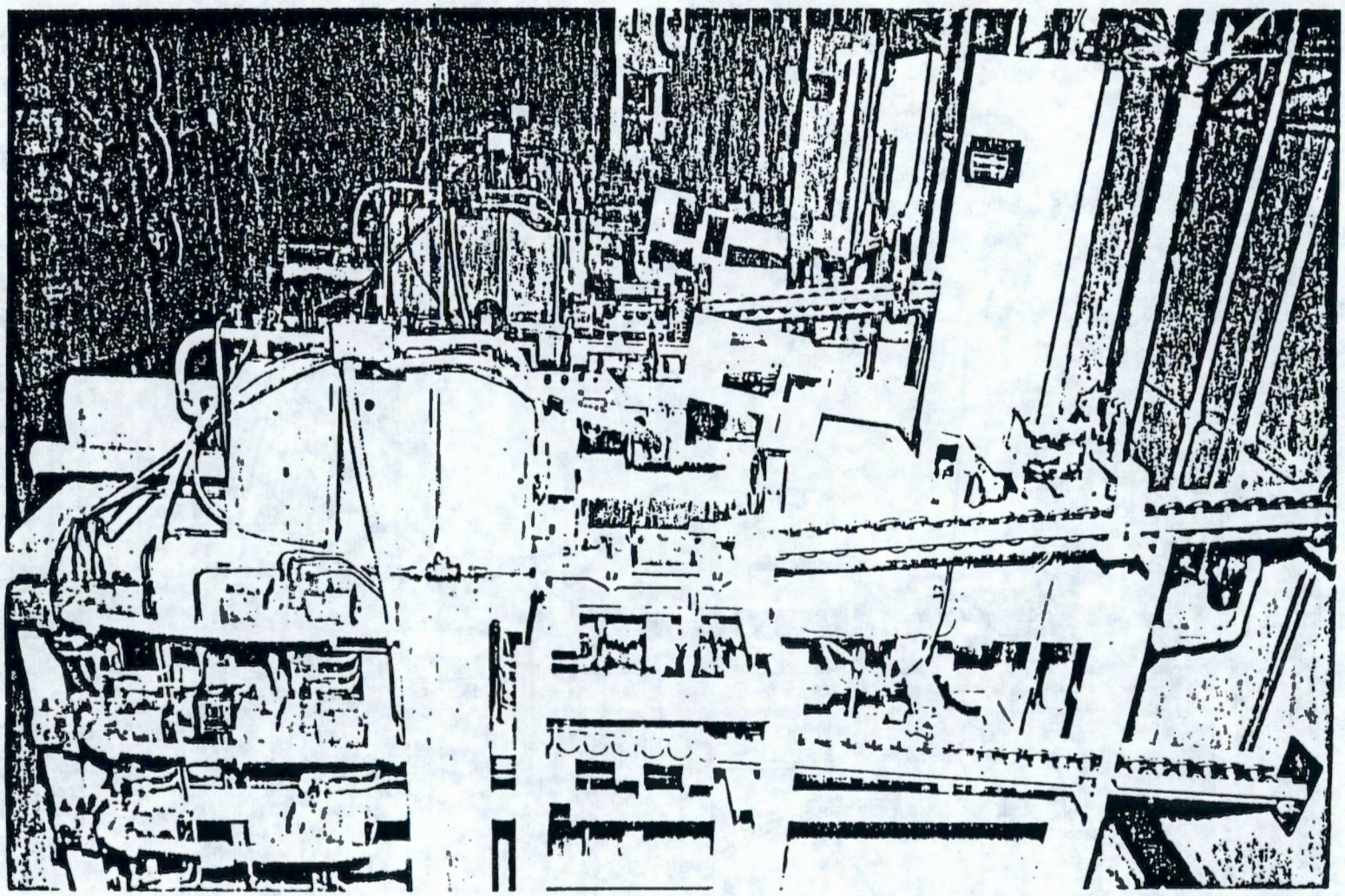

FIGURE 43

Automatic Welders

The five automatic welders are expected to be ready for production use in January, 1959. The fuel elements are automatically fed to and from the welder by "skate-wheel" conveyors.

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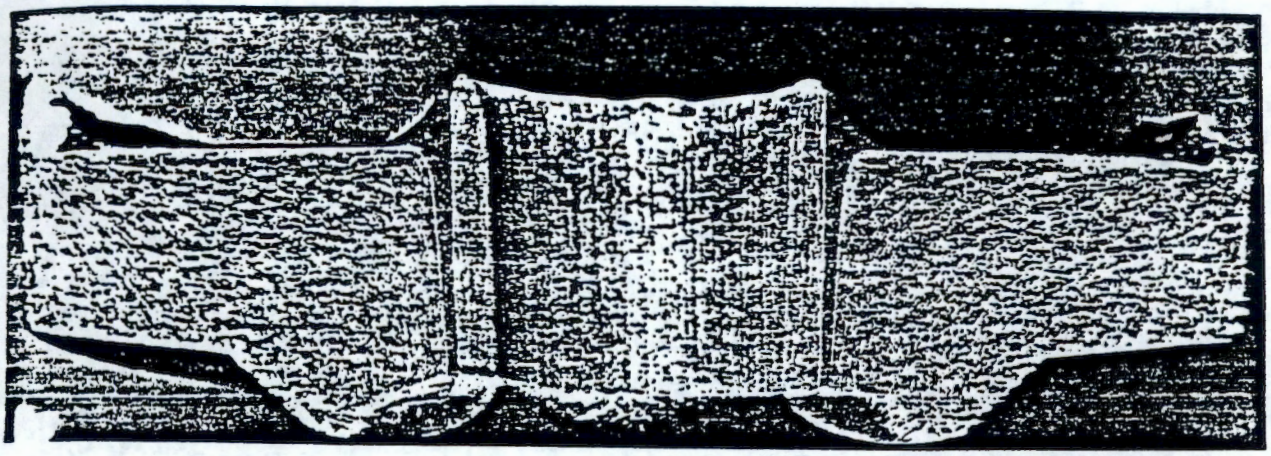
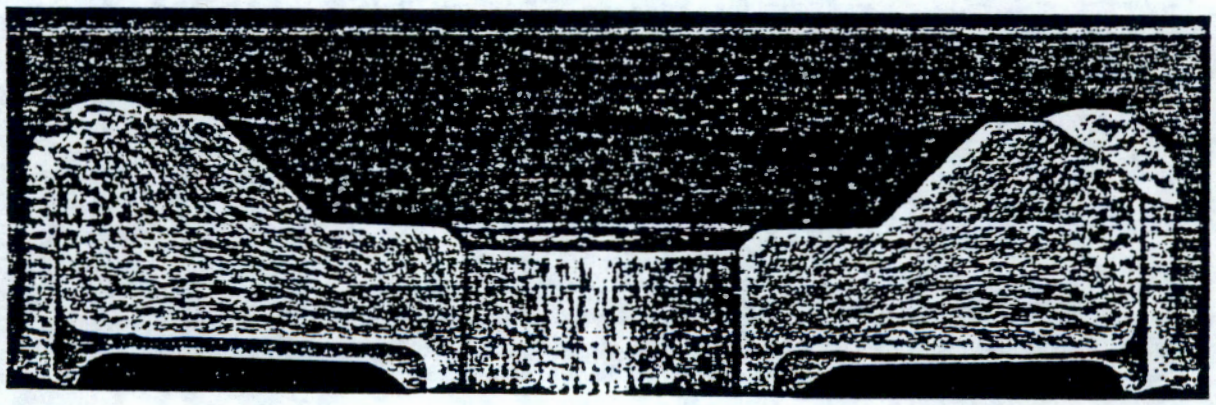
HTR OPERATIONS



A. Cross-Section of Can Base Showing Base Weld



B. Cross-Section of Cap Wafer Showing Cap Weld

FIGURE 44

Examples of Typical Base and Cap
Welds on I & E Fuel Elements
Al-Si braze metal appears as darkened areas between the can and cap-spire. About 4X

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WITH EXCEPTIONS

[redacted]

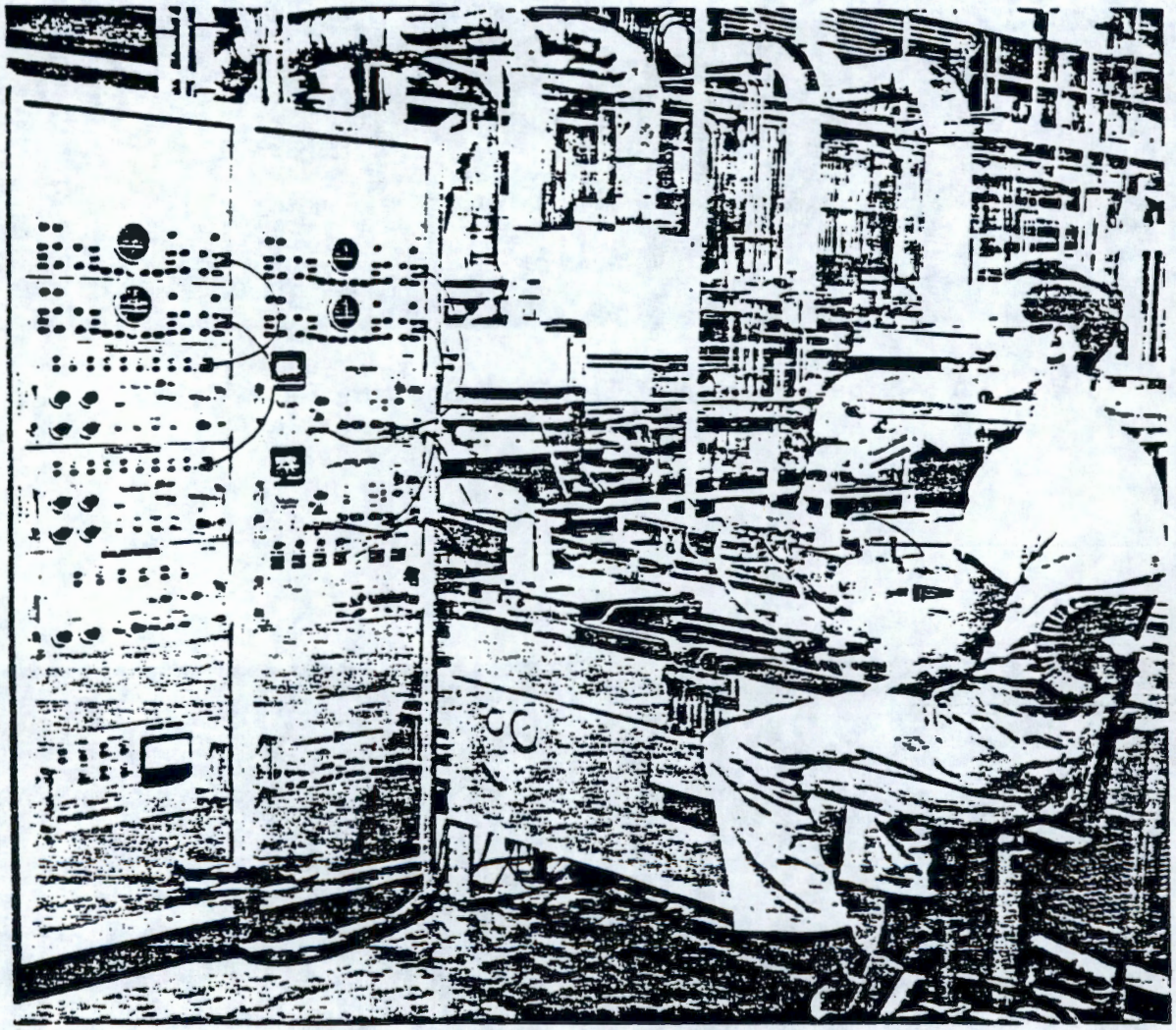

FIGURE 45

Bond and Penetration Tester

The five bond and penetration testers examine I & E fuel elements internally and externally for completeness of bonding and for residual aluminum jacket wall thickness. The fully automatic testers separate the reject fuel elements from the good pieces.

[redacted]

ASC-GE RICHLAND, WASH.

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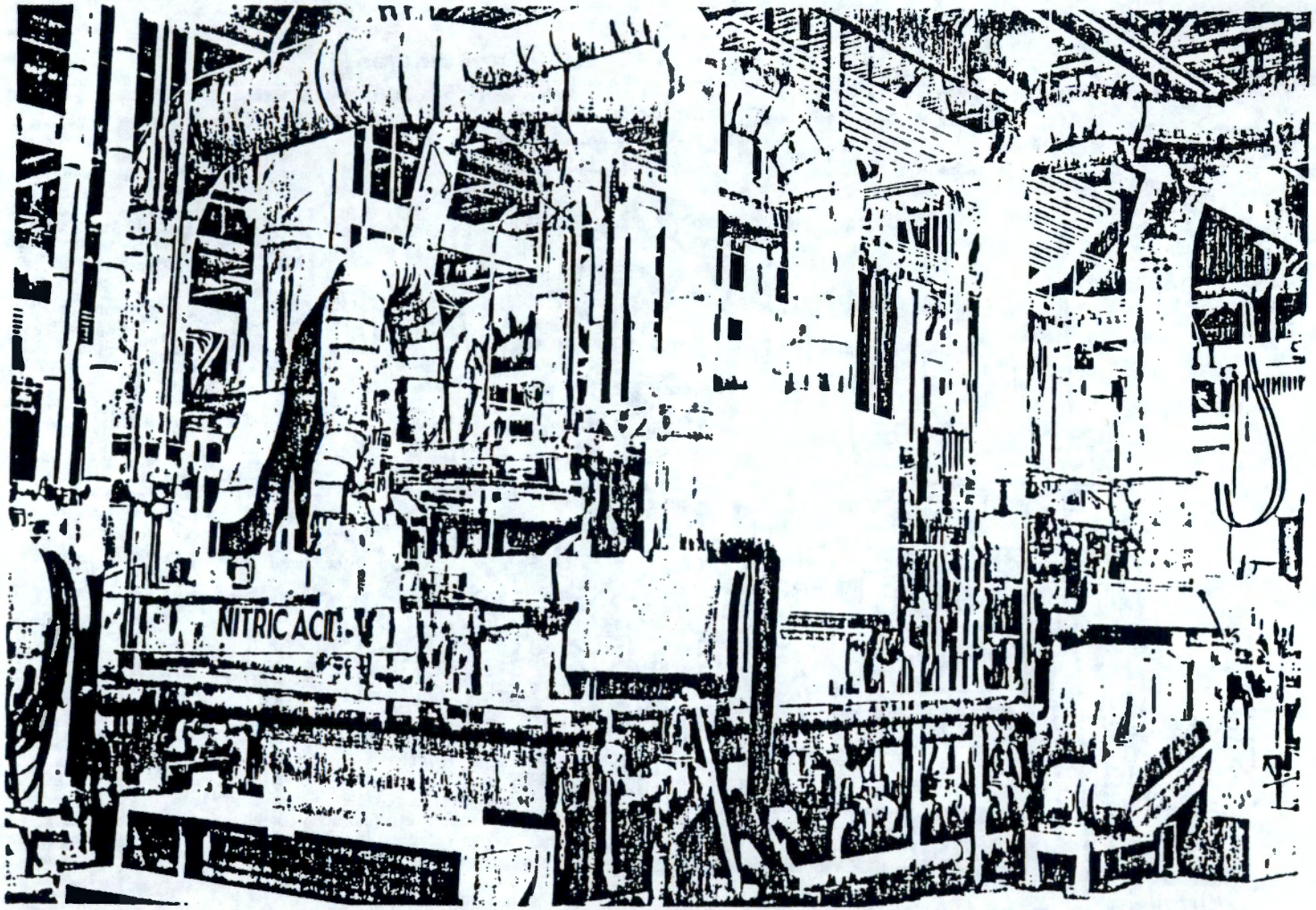

FIGURE 46

Fuel Element Etch Machine

Fuel elements are automatically conveyed through the etch tanks in the two etch machines. The only manual operations are to load and unload the etch racks (not shown).

ABC-GE RICHLAND, WASH.

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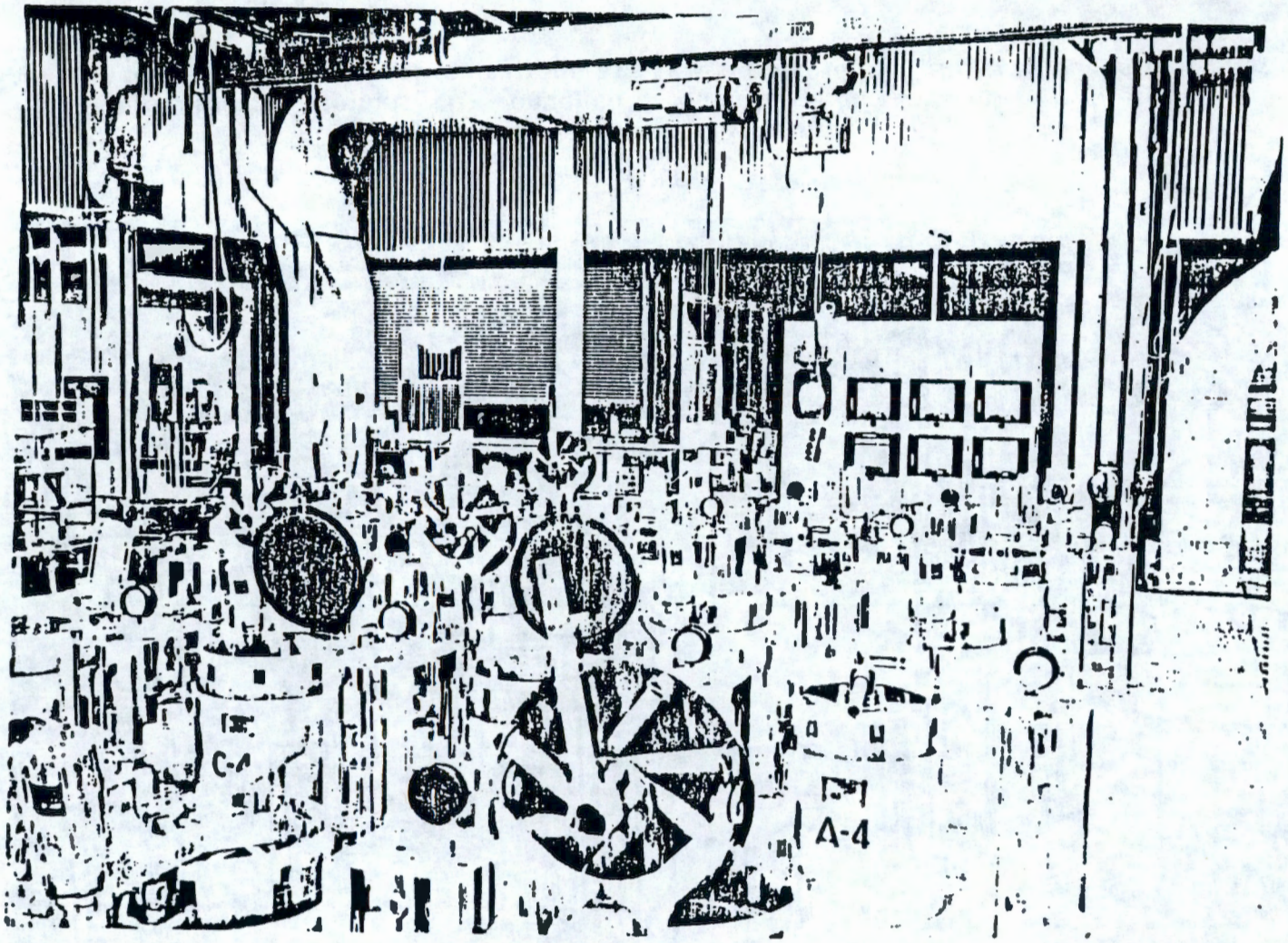

FIGURE 47

Autoclave Area
This view shows the 36 autoclaves used for steam or water autoclaving of fuel elements.

HP 1874

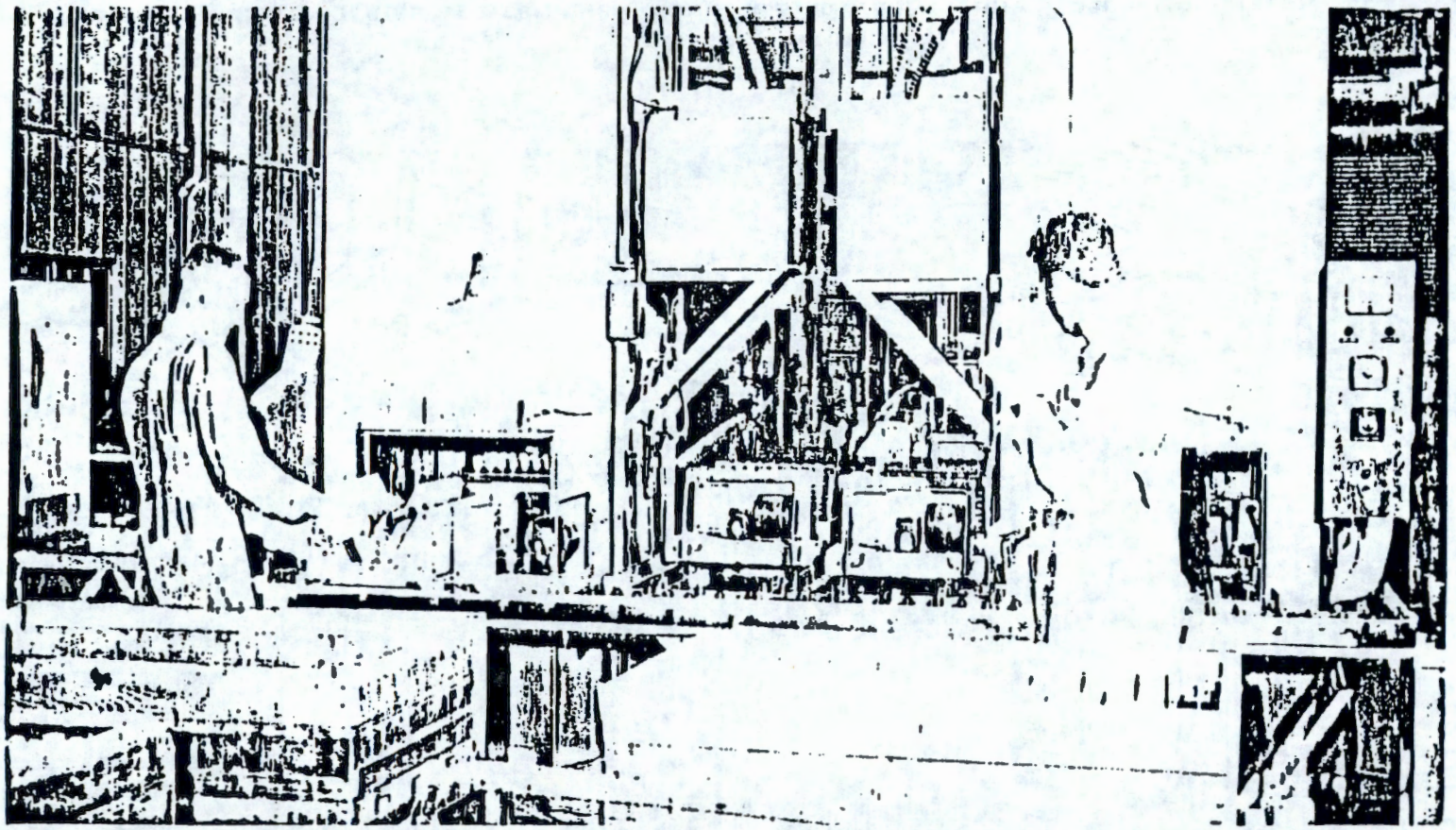

FIGURE 48

Radiograph Machines

These two machines are used to radiograph the cap welds on fuel elements. The radiograph trays (18 pieces per tray) are loaded on the far side of the machines and pass through the machines to the unload area (as shown). The fuel elements are placed and stored in storage pallets (foreground).

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ARC-42 RICHLAND, WASH.

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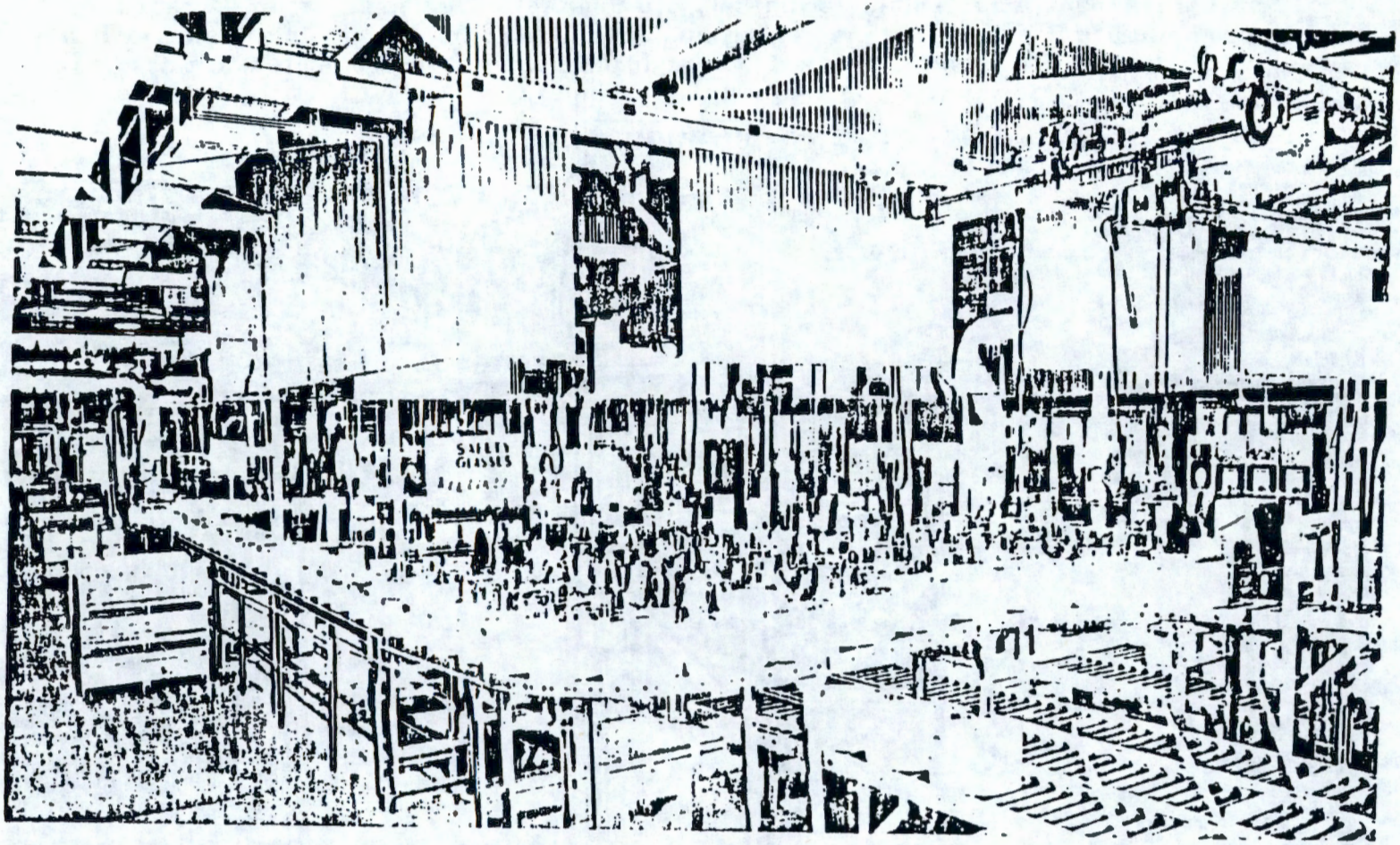

FIGURE 49

Empty Autoclave Basket Return Conveyor

Empty autoclave baskets are returned from the final fuel element inspection station (at right) to the etch machines (far background) on a conveyor as shown. Loaded autoclave baskets are handled on roller conveyors at the final inspection station.

ABC-GE RICHLAND, WASH.

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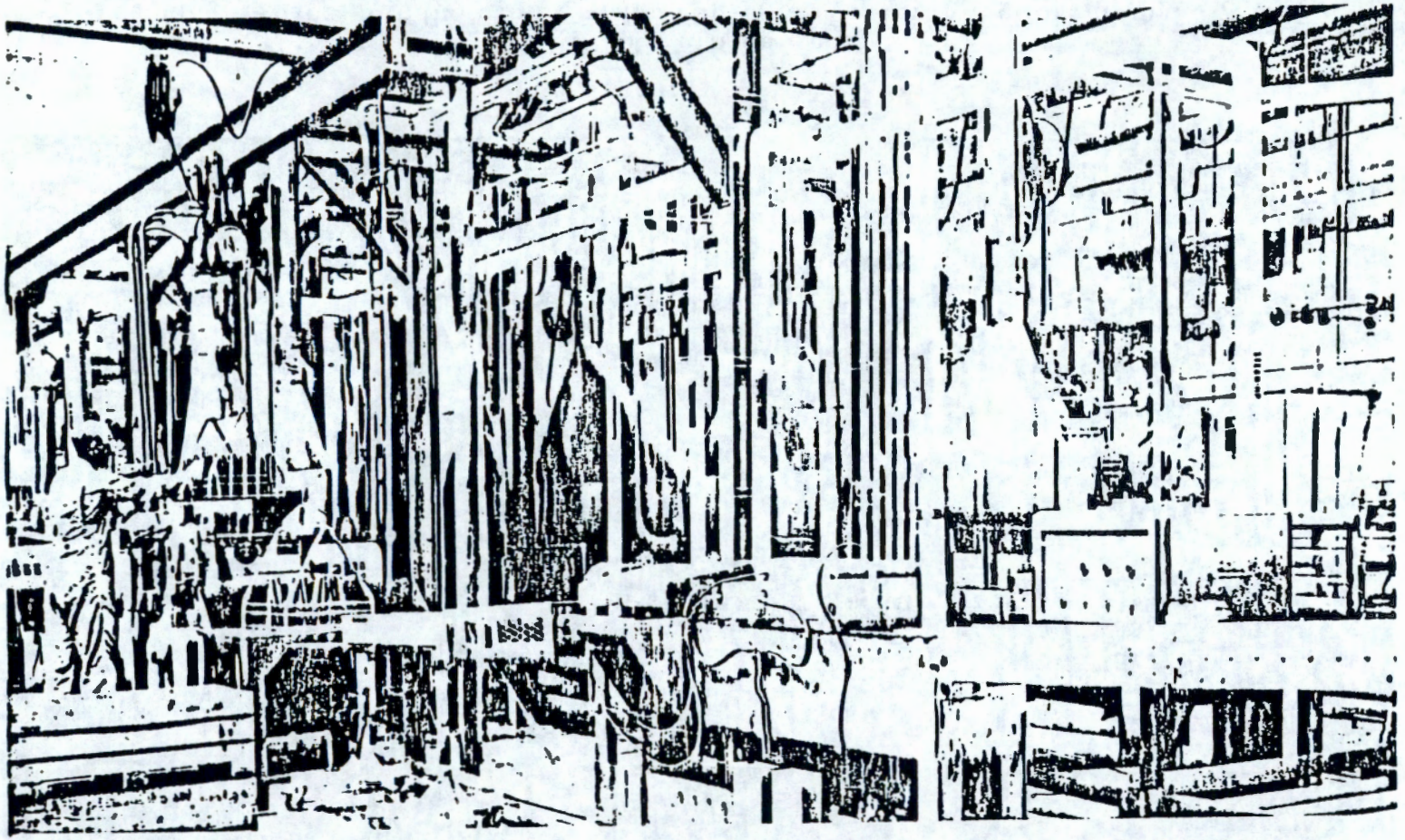

FIGURE 50

Pilot Plant Component Preparation Area

The core transformation tester is in the center foreground with the core etch line at the left. The aluminum component cleaning line is in the background. Also included in this area is a sleeve cleaning line (not shown).

AEC-GE RICHLAND, WASH.

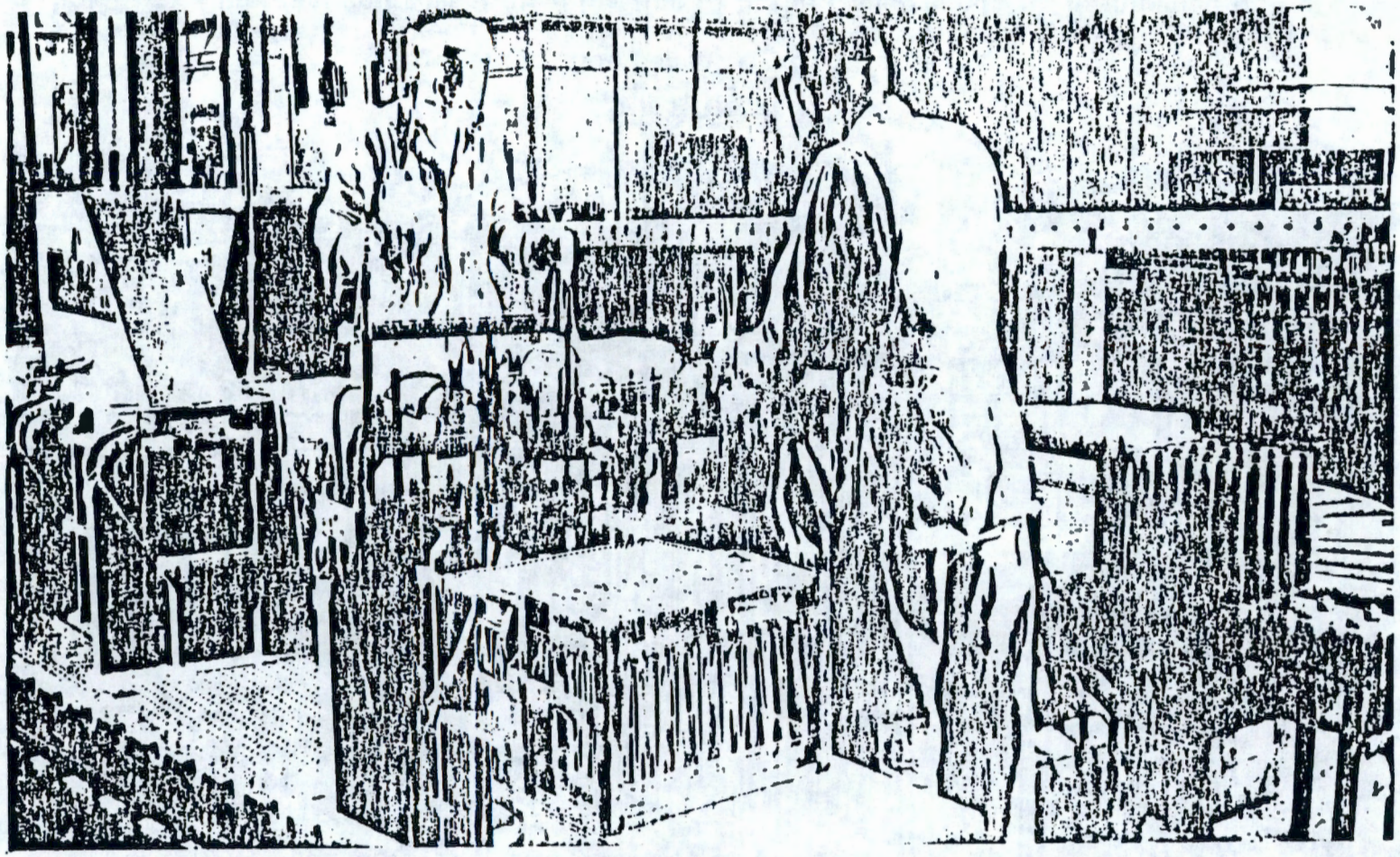

FIGURE 51

Pilot Plant Furnace Area

The canning furnace is in the center with a cap-spire basket in the foreground. A tray of can-sleeve assemblies is shown at the right. The duplex furnace can be seen in the background. Roller conveyors transfer components from the cleaning area to the furnace area.

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AEC-GE RICHLAND, WASH.

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WITH DELETIONS

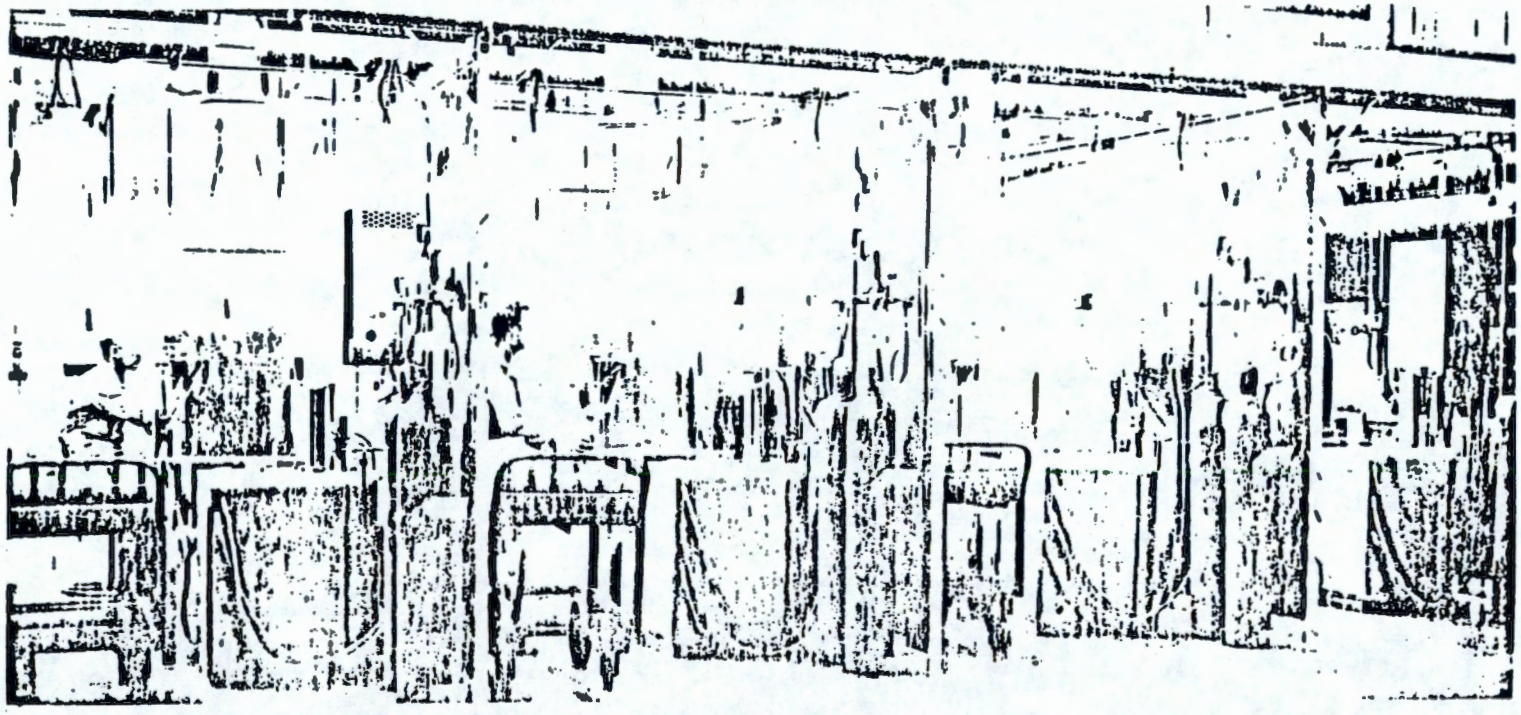

FIGURE 52

Pilot Plant Welding Area
Manually operated inert-gas-shielded A.C. arc welders without filler metal additions are used in the Pilot Plant.

AEC-GE RICHLAND, WASH.