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**EVALUATION OF VACUUM-CANNED
AND HOT-PRESS FUEL ELEMENTS**

PT IP-44A AND IP-45A

E. A. SMITH

OCTOBER 15, 1958

HANFORD LABORATORIES

**HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON**

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EVALUATION OF VACUUM-CANNED AND

HOT-PRESS FUEL ELEMENTS

PT IP-44A AND IP-45 A

by

E. A. Smith

Fuels Development

Reactor and Fuels Research and Development Operation

October 15, 1958

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

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EVALUATION OF VACUUM-CANNED AND
HOT-PRESS FUEL ELEMENTS
PT IP 44A AND IP 45 A (1, 2, 3, 4)

INTRODUCTION

As new designs, geometries, and procedures for fabricating experimental fuel elements are developed, it becomes necessary to determine how well each new product fills the need which prompted its development. While the criteria for satisfactoriness vary with the type of fuel element, there is one criterion that is common to all types designed for use in heterogeneous reactors: the elements must withstand irradiation in the reactor for the required period without jacket rupture or excessive change in dimensions. To learn whether a new type of element meets this and other requirements, a statistically significant number of representative samples must be subjected to, first, comprehensive screening tests designed to insure trouble-free performance in the reactor; next, a long-term irradiation exposure equivalent to or exceeding that which will be normal for that type of element; and finally, a thorough examination to determine the extent of quality loss resulting from the irradiation.

This report discusses the application of the foregoing philosophy in the evaluation of two lots of experimental fuel elements fabricated by unconventional procedures.

-
- (1) Van Wormer, F. W., Production Test IP-44-A, Irradiation of Vacuum Canned I & E Fuel Elements, HW-50125, May 7, 1957.
 - (2) Smith, E. A., Proposal for a Production Test to Evaluate Vacuum Canned Fuel Elements, HW-48081, January 31, 1957.
 - (3) Foust, W. E., Design of PT IP-45-A, Irradiation of Hot-Press Canned Fuel Elements, HW-48238, February 5, 1957.
 - (4) Van Wormer, F. W., PT IP-45-A, Irradiation of Hot-press Canned Fuel Elements, HW-49746, April 22, 1957.
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SUMMARY

Test lots of eight inch I & E fuel elements* fabricated by the Hot-press process and by the AlSi bond, vacuum-canning process, together with lead-dip canned control slugs, were irradiated to progressively increasing exposures up to 800 MWD/T, without incidence of failure. Following each discharge the irradiated slugs were examined, both before and after cleaning, in the C-basin viewing facility. Specimens which showed the greatest damage in these examinations were subjected to detailed study in the Radiometallurgy Laboratory. The results of these studies led to the following conclusions:

1. There was no outstanding difference among the three types of fuel element with respect to vulnerability to reactor operating conditions.
2. The anodized coating applied to the hot pressed slugs appeared beneficial in reducing the incidence of surface mars, scuffing, and embedded particles. However, where the anodized coat was broken, this protection was lost. The few instances of embedded particles in hot-pressed jackets appeared at least as badly corroded as any of the vacuum-canned or control slugs.
3. The finished diameter selected for the I & E slugs is too large with respect to the tube ID. The restricted annulus opposite the ribs thus affords insufficient cooling capacity, with the result that slugs in the downstream half of the tube, regardless of the process used in their fabrication, become overheated and develop on their upper sides the boiler-scale deposits typical of "hot-spot" failures. Attendant damage from intergranular corrosion accounts for the greatest part of the quality loss sustained by the slugs in these tests.

*The particular type of fuel element covered by this study is the tubulated, aluminum jacketed, right circular cylinder known locally as the "I&E Slug". Inasmuch as the data developed herein is inapplicable to many types of fuel element, the general term "fuel element" is used only sparingly and the more specific term "slug" is employed in accordance with traditional usage.

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4. Another cause of localized corrosion is the presence in the jacket surface of embedded particles, suspected of being the fly-ash commonly encountered in the fabrication and storage area. Although many observed embedded particles in the irradiated slugs appeared inert, there was rather severe corrosion around others. The severity of attack was generally greater when the embedded particle lay within a "hot-side" zone.
5. The conditions which caused wide differences in ultrasonic test results on the irradiated slugs apparently had no effect on the degree of quality deterioration they experienced. Slugs which gave indication of poor bonding in the post-irradiation ultrasonic test appeared to have suffered no damage as a result of irradiation. (It is, of course, possible that the effect would have been more evident if the slug had occupied the position of maximum severity in the tube.)
6. Using the rate of weight loss as an index, the generalization may be drawn that there is a sharp increase in the tendency toward jacket deterioration from the center of the tube downstream; the No. 8 position (beginning numbering at downstream end) is the position of maximum severity.
7. With respect to longevity-promoting features resulting directly from processing techniques, none of the three types of fuel element treated in these tests appears to be outstandingly superior to either of the other two. The fact is emphasized that the properties of a fuel element which promote its survival during long-term irradiation are not necessarily dependent upon the nominal process of fabrication. The true measure of superiority of a fuel element fabrication process lies in its ability to provide the required properties consistently, uniformly, and economically in a very high percentage of product output.

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HISTORICAL BACKGROUND

On November 5, 1951, at a meeting held at Hanford, attended by representatives of numerous Atomic Energy installations throughout the United States, the need was expressed for a more durable fuel element than the type being fabricated in regular Hanford production at that time. The principal undesirable aspect of the then-current triple-dip canned Al-Si bonded fuel element was described as being the brittleness of the bond, with resulting impermanency of its heat transfer properties during irradiation. In keeping with this theme, in the ensuing months several alternate methods of attaching the jacket to the core were experimentally tried.

From these experiments two philosophies emerged as being likely to lead to success. One involved the development of an entirely new bonding medium together with an appropriate canning process; the other, the development of a new canning process retaining the Al-Si bonding medium with its proved advantages, but eliminating most of the disadvantages associated with hot dip canning. The former philosophy was most favored, and a large development program to produce a satisfactory Hot-press canned slug was launched. After several reverses, a satisfactory technique was found leading to the production of the test lot of slugs with which this report is concerned. (PT-IP-45-A)

The principal aim of the Vacuum-canning process was to reduce the number of critical process variables affecting canned slug quality, and thus to insure high quality in a very high percentage of the output. A minor development program for the improved Al-Si bonding process was carried out, permitting the preparation of the test lot of slugs for PT-IP-44-A. While the vacuum process was being developed, the establishment of improvements and tighter controls on the standard manufacturing process resulted in considerable progress toward accomplishing the same desired ends, so that the justification for further development of this promising new process was largely removed. Hence, despite the excellent behavior of the vacuum canned material in the present test, no further development of the process is contemplated.

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DETAILS

The two experimental types of fuel element covered by the subject production tests were designed to provide high quality (i. e., resistance to deterioration as a result of irradiation) in a greater-than-normal percentage of output. The various aspects of their objectives and of their evaluation are described below.

I. The Hot-Press Canning Process⁽⁵⁾ (PT IP 45A)

Briefly, this process involves (a) plating the uranium core with a thin coating of nickel to bar U-Al diffusion during irradiation; (b) mechanically sizing properly cleaned jacket components around the core, and (3) finally bonding the jacket to the core by end-loading in a closed die with heavy pressure at high temperature.

Benefits believed to derive from this method of canning include:

- a. A bond between jacket and core that remains unharmed under severe mechanical and/or thermal stresses.
- b. A nickel layer which acts as a diffusion barrier between aluminum and uranium; effective up to 300 C.
- c. Improved reactivity (as compared to hot-dipped elements) by virtue of increased uranium core diameter, with standard OD and can wall thickness, but reduced bonding layer thickness.
- d. Complete elimination of gas voids in the bond.
- e. Diffusion bond (with hot-worked metal) at interface between jacket and cap at closures.
- f. Hard, anodized surface to reduce mechanical damage from handling.

A lot of slugs was fabricated by this Hot-press process for testing and evaluation. Following fabrication, they were non-destructively tested⁽⁶⁾ for pertinent quality features as described below:

- a. Closure soundness, by visual observation, dye penetrant methods, radiography, and autoclaving.

(5) Foust, W. E., Hot-Press Canning at Hanford, HW-48329, February 11, 1957.

(6) Smith, E. A., Pre-Irradiation Inspection Tests - Hot-Pressed Fuel Elements, HW-48330, February 15, 1957.

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- b. Bond Test,* applied to both outer jacket wall and inner tube wall.
- c. Dimensional measurements, including warp.
- d. End cap thickness, by X-ray Fluoroscopy.
- e. Wall thickness, by Vectorscope.
- f. Nickel layer thickness and distribution, by Magnetic Nickel Mapper.
- g. Surface quality, by visual examination for surface inclusions, mechanical damage, closure defects, corrosion resulting from autoclaving.
- h. Reactivity, by use of 305 Test Reactor.

In addition, destructive tests were applied to verify the results of the non-destructive tests and to determine general quality with respect to:

- a. Uranium grain size, by metallography.
- b. Grain orientation, by Sonic Orientation Test on stripped cores.*
- c. Nickel-uranium adhesion and interfacial condition.
- d. Nickel-aluminum adhesion and interfacial condition.
- e. Resistance of nickel layer to water attack, by chemically drilling 1/16-inch diameter holes through the jacket wall to the nickel layer, then exposing the drilled element to water at 170 C, 100 psi, for 130 hr.
- f. Resistance of cladding system to lateral propagation of attack, by drilling 1/16-inch holes some down to the barrier layer, and some completely through the jacket and sweater coat into the uranium; then exposing the drilled element to water at 170 C, 100 psi, for up to 130 hours.

*Ultrasonic tests gave questionable results. Almost without exception, the hot-pressed elements were classified as "bad" by the test instrument; yet samples destructively tested were found to have perfectly sound bonds. Hence, the use of the ultrasonic test on hot-pressed elements was abandoned in favor of a modified Frost Test which culled out elements with eccentric core placement, excessively thick nickel plating on the ends, and/or zones of poor heat transfer between core and jacket.

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g. Adhesive qualities of cladding and general bond quality, by Chisel Test.

h. Hydrogen analysis of stripped specimens.

II. The Al-Si Bond, Vacuum-Canning Process⁽⁷⁾ (PT IP 44A)

The conditions of this process are similar to those of the standard Hot-dip canning process except that: (a) the uranium core is preheated by induction in a vacuum instead of in a lead bath, (b) the molten bonding medium is added to the assembly of components after the latter have been heated to a temperature at which wetting with the bonding medium will take place, and (c) the molten bonding medium is forced into the evacuated spaces between the assembled components by gravity plus the pressure caused by readmission of atmosphere into the assembly chamber.

Advantages believed to result from the use of this process are:

- a. Voids and gas pockets in bond and braze are virtually eliminated.
- b. The braze may be made with Al-Si uncontaminated by uranium or metal dissolved from canning tools.
- c. The time of contact of molten bonding medium against the components may be made very short, thus making for a thin, relatively infrangible compound layer, and minimizing the penetration of the bonding medium into the can wall by dissolution.
- d. In all other respects the product has the same characteristics as that of the standard canning process.

A lot of slugs was fabricated by this vacuum canning process for testing and evaluation. Following fabrication, they were non-destructively tested for pertinent quality features⁽⁸⁾ as described below:

- a. Closure soundness, by visual observation of braze line after facing; observation of welding operation on each individual element, plus close scrutiny of weld bead after welding; radiography of closure region; autoclave test.

(7) Powers, C.S., Vacuum Braze Canning, HW-48008, January 14, 1957.

(8) Smith, E.A., Pre-Irradiation Inspection Tests - Vacuum Canned Fuel Elements, HW-49004, March 12, 1957.

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- b. Bond soundness by ID and OD autoradiography; ID and OD ultrasonic bond test;* ID and OD Frost Test.
- c. Wall penetration by Eddy current tester. (In addition, destructive etching of statistical samples and metallographic methods were used to verify the results of the non-destructive tests.)
- d. Dimensional measurements, including warp.
- e. End cap thickness, by X-ray fluoroscopy.
- f. Surface quality, by visual examination for surface inclusions, mechanical damage, closure defects, corrosion or swelling resulting from autoclaving.

In addition, destructive tests were applied to representative samples to verify the results of non-destructive tests, and to determine general quality with respect to:

- a. Uranium grain size, by metallography.
- b. Grain orientation, by Sonic Orientation Test on stripped cores.
- c. Compound layer condition, (thickness, distribution, purity, etc.) by metallography.
- d. Bond strength, adhesion, frangibility by chisel test.
- e. Vulnerability of bonding layer to attack in 170 C water, by water autoclave test.
- f. Resistance of cladding system to undercutting, by Boiling Test and Water Autoclave Test.
- g. Hydrogen analysis of stripped specimens..

*Ultrasonic tests gave questionable results. Almost without exception, the vacuum canned elements were indicated "bad" on at least one pass through the instrument, although on repeated passes, they would frequently be classed as passable. Elements accepted for charging in the reactor were required to be passed as acceptable by this instrument at least once, and also to have been acceptable in Frost Tests.

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IRRADIATION

Sixty-four slugs from each of the two above-described test lots, having successfully passed all the foregoing non-destructive tests, were loaded into eight tubes in C-Reactor, alternately with a similar number of lead-dip canned eight-inch I & E control slugs.* Prior to charging, a record was made of the weights of the test pieces in the hot-press canned group for use in determining the extent of jacket corrosion (if it should appear excessive). One tube from each group was discharged according to schedule at ~ 400 MWD/T both groups having been charged at the same time,** and irradiated under similar operating conditions at ~ 50 KW/ft.

Later, another tube of each PT was discharged on schedule at ~ 600 MWD/T; still later the remaining two tubes of each test were discharged at ~ 800 MWD/T.

The scheduled irradiation period was completed without untoward incident.

Post-Irradiation Examination

Following discharge, the irradiated test and control slugs were examined as thoroughly as possible with available facilities in the examination basin, 105 C.

Tests applied, observations, and interpretations of the observations were as follows:

1. Slugs discharged 9-17-57 at ~ 400 MWD/T.

Each element was "weaseled", placed on the underwater manipulator, and scanned with the variable power periscopic microscope.

* The control elements for both PTs, IP 44A and IP 45A, were lead-dip canned slugs left over from PT 313-83 MT.

** All tubes were charged June 28, 1957.

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A few of the downstream slugs, both test and control, and in both tubes, were seen to have developed a calcareous scale on the upper half ($\sim 180^\circ$ opposite the ribs) of the cylindrical surface. On most of the affected slugs, the scaly area was of fairly uniform width over the entire length of the uranium component, stopping sharply at the plane of juncture of core with end cap. On two of the Vacuum-canned slugs (PT IP 44A) the scaly area was confined to two smaller cigar shaped areas of typical "hot-spot" appearance, both $\sim 180^\circ$ opposite the ribs. Subsequent etching in chromic-sulfuric acid to remove the film revealed a band of slight pitting attack surrounding the more heavily scaled central area, which was not completely denuded by the etching.

None of the elements appeared to have suffered appreciably as a result of irradiation; except for the scaly deposit, all appeared to be in as good a condition as before charging. It was noted that the hot-pressed slugs of PT IP 45A were in general less scuffed or marred than either the control groups or the vacuum canned group. This is attributed to the mechanical protection afforded by the anodized hard coat applied to the jacket surface of the hot-pressed lot just before shipping to be charged.

The underwater ultrasonic bond tester was used to scan some of each type of element. This instrument indicated, for the control slugs, generally sound bonds after irradiation, although the mechanical defects on the surfaces led to many spurious indications. The vacuum canned slugs appeared, with respect to behavior in the ultrasonic test, unchanged by irradiation; they appeared extremely poor on the instrument just as they had before charging. (Here again occasional strong readings on the instrument were found associated with surface defects.) The hot-pressed slugs, however, appeared to have been favorably affected by the irradiation. Instead of the fuzzy effect characteristic of their behavior in ultrasonic tests prior to charging, they now gave indication of having an extremely sound bond.

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Conclusions from the Foregoing Observations

- a. With respect to loss of quality as a result of ~ 400 MWD/T exposure, there appears to be little difference among the three types of I & E fuel elements being compared (lead-dip canned, vacuum canned, hot press canned). With one exception, (the corroded spot surrounding an embedded particle on a control slug) they appear not to have suffered appreciably from approximately three months' exposure in the reactor.
- b. The OD chosen for the I & E element appears somewhat too large for the ID of the standard C-Reactor tube. The downstream half of the tube operates at too high a temperature, particularly in the portion of the annulus opposite the ribs. This leads to the deposition of a "boiler-scale" on the uppermost side of the downstream slugs, which further retards heat transfer through that area, and tends to promote jacket damage at that location.
- c. The acoustic properties of lead-dip canned and vacuum canned slugs, as measured by ultrasonic methods, appear substantially unchanged by irradiation (up to 400 MWD/T), while the acoustic impedance of the nickel sweater-coated hot-pressed variety appears to be greatly reduced by irradiation. It is, of course, possible that the apparent change is due to other causes such as differences between the pre- and post-irradiation measuring instruments with respect to characteristics and adjustments.
- d. The difference in acoustic properties exhibited by the three types of fuel element apparently do not correlate with properties that affect vulnerability to irradiation conditions; in other words, the conditions which caused wide differences in underwater ultrasonic readings on irradiated slugs had no apparent effect on the degree of quality deterioration experienced by the elements as a result of irradiation.

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Slugs Discharged at ~ 600 MWD/T.

These slugs were examined in a manner similar to those of the earlier discharge, but in greater detail. The observations confirmed and amplified the results of the previous study.

- a. Hot-sides or large boat-shaped hot spots were in evidence on every slug downstream of position 15 to position 2 in both tubes. There appeared to be no general difference in severity among the three types of elements (lead-dip controls, vacuum canned, and hot-pressed canned test pieces) in this respect.
- b. Around the fringes of the hot zone on each affected slug, accelerated corrosion of the jacket was found in the form of tiny pits; the general appearance of the aluminum surface in the hot zone was suggestive of incipient intergranular corrosion. However, the degree of attack was very light, and the general quality appeared to have suffered very little as a result of the ~600 MWD /T exposure.
- c. The effect of embedded particles in the jacket surfaces was beginning to show up, particularly among the lead-dip controls and the vacuum canned test elements. These particles appear to be of two types: tiny black specks typical of as-received can inclusions and sleeve scale; and larger, spongy appearing black masses suggestive of the fly-ash that pervades nearly all 300 Area premises. The latter type caused the most damage. (Figure 1) The aluminum can surface immediately surrounding such embedded particles was usually more heavily corroded than the more remote regions of the jacket wall, especially when the particle happened to lie in a "hot side" area. The occurrence of this condition appears to be the greatest menace to longevity of the elements. One lead-dip control slug had developed an alarmingly deep pit near the cap end around a small embedded particle in the hot side zone; the chances of continued survival of this slug under operating conditions appear relatively poor.

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FIGURE 1

View of One of the Largest Embedded Particles

This one, found in a control slug, had comparatively little surrounding corrosion. Worse ones, from a corrosion standpoint did not show up well in pictures.

One of the control slugs bearing four embedded black particles was submitted to the Radiometallurgy Laboratory, where, it was hoped, tests might be applied to afford positive identification of the embedded material. However, repeated attempts to isolate the particles were unsuccessful, and they can be identified as fly ash only on circumstantial evidence.

- d. The resistance to scuffing and mechanical damage provided by the anodized coating on the hot-pressed slugs is better illustrated as greater numbers of samples are examined in comparison with un-anodized elements. The greater surface hardness of the

coating may account for the low incidence of embedded black particles in the hot-pressed variety. Since the most severe apparent damage to the unanodized surface is that occurring in the locality of the embedded particles, it might be found profitable to anodize standard production slugs for protection against this type of defect.

- e. One hot-pressed, one vacuum canned, and one control element for each PT, (total, four samples) showing the most pronounced hot side effects, were chemically stripped in the C-basin viewing facility to determine whether any damage to the uranium core had occurred as a result of the uneven heating. Subsequent examination brought out no evidence of core surface change on any of them; all looked exactly like chemically stripped unirradiated cores.
- f. No appreciable distortion was apparent in any of the discharged slugs. The underwater warp-measuring facility was not available at the time these screening examinations were done; however, the lack of "wobble" as the slugs were rotated about their longitudinal axes indicated that the degree of permanent warp was slight at most. Also there was no evidence of galling on the jackets such as would be caused by discharging if there were distortion of a magnitude greater than the annular space between element and tube. Warp measurements taken later, by the Post-Irradiation Examination group and analyzed by the Industrial Statistics group, ⁽⁹⁾ indicate no significant differences among the three lots of slugs with respect to dimensional change due to irradiation.

Slugs Discharged at ~ 800 MWD/T

Observations made on these elements were essentially the same as described for the 600 MWD/T group; their residual quality, as judged before cleaning, from appearance through the underwater viewer, seemed little worse in general than that of the 600 MWD/T group.

(9) Jaech, J. L., Analysis of Dimensional Data from PTs IP-44 A and IP-45 A - HW-56031 RD, May 12, 1958.

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- a. The "boiler-scale" deposit over the hot sides and hot spots appeared somewhat heavier, (Figures 2, 3, and 4) especially on the hot-pressed elements, which had operated at higher specific power because of their larger core diameter. When subsequently cleaned in chromic-sulfuric acid, these burnt-lime regions were found to more strongly attacked than on the previous groups and in some cases their removal left the jacket with a rugged contour.
- b. Corrosion damage around embedded black particles appeared generally more severe than on earlier discharges of this test material.
- c. One hot-pressed specimen, (Figure 4) with three closely-spaced embedded particles lying in a pronounced hot-side zone, appeared rather severely corroded after cleaning. This specimen was submitted to the Radiometallurgical laboratory for detailed study and will be discussed later in this report.
- d. In general, the entire lot: hot-pressed, vacuum canned, and lead-dip controls, appeared to have suffered relatively little loss of quality as a result of the six months (800 MWD/T) exposure. Such quality loss as was apparent was associated with the embedded particle and hot-side conditions which are independent of the method of fabrication.
- e. One of the principal aims of this production test was to determine whether irradiation tends to cause deterioration of the heat-transfer properties of elements canned by the various processes. It was proposed to do this by making use of the γ -heating effect of freshly discharged elements. With heat being dissipated continuously from the irradiated element, and with the basin water in which it is submerged acting as a heat sink, regions of the jacket surface overlying zones of poor heat transfer between the uranium core and the jacket should be colder than the surrounding areas through which the heat is flowing readily. Thus, scanning the surface of the irradiated slug

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FIGURE 2

Lead-dip control piece for PT IP-45 A (Hot-press). Tube C-1587, position 13, after ~800 MWD/T exposure. Entire side of slug opposite rib shows evidence of hot operation; "hot-spot" is concentrated near downstream end of slug.

FIGURE 3

Vacuum-canned test piece for PT IP-44 A, Tube 3366, position 11. After ~ 800 MWD/T exposure. Illustrates a condition similar to that shown in Figure 2. Hot spot is concentrated near upstream end of slug.

FIGURE 4

Hot-press-canned test piece, PT IP-45 A. Tube 1689, Position 8. After ~800 MWD/T exposure. Shows appearance of the slug later studied in Radiometallurgy, as viewed after cleaning, using the C-Basin viewing facility. Embedded particles which aggravated corrosion are visible about 2-1/2 inches from left end of slug.

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with a temperature-sensitive element could be expected to reveal any underlying zones of poor heat transfer. Since heat transfer was known to be satisfactory before charging, as shown by Frost Test results, a bad heat-transfer zone after irradiation may be assumed to have been caused by something taking place during charging or irradiation.

Unfortunately, facilities in the basin where this experiment was to be performed were undergoing repairs at the time the slugs were discharged and they had cooled too much to apply the temperature-differential test before the facilities were again available.

DISCUSSION

It might be argued that since none of the three varieties of fuel element in the tests failed during irradiation, and since little, if any, difference in residual quality can be distinguished among them, these production tests are inconclusive with respect to which is the best process for the fabrication of fuel elements. However, it should be pointed out that:

(1) These tests were not designed to settle the question as to which is the best canning process, but rather to determine whether any typical features of the product of the various fabrication processes were points of weakness during irradiation. Final judgment as to the relative superiority of a given process can only be passed after a long-term comparison against competitive processes, and even then, there is strong likelihood that variability in some apparently trivial item can swing the balance in favor of a competitor. It is only where outstanding differences in irradiation behavior, influenced by the fabrication process, are observed that they can be properly accredited in a small-scale test.

(2) Using an alternative criterion; viz., the occurrence of rupture during irradiation as an index to the suitability of the fabrication process, may lead to spurious conclusions, especially where small numbers of test elements

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are involved. As illustrated in the present instance, the slugs which came nearest to failing were those which had embedded particles in the surface. These particles were picked up between final inspection and charging, and bear no relation whatever to the fabrication process. However, if any one instance had been only a little more severe, resulting in actual failure during the irradiation, the fabrication process by which that unfortunate individual was made would have been severely compromised.

(3) Not all new fuel fabrication processes are designed specifically to make substantial improvements in failure rate. Specific goals are numerous and varied, and include such concepts as:

- a. Providing a "fail-safe" mechanism whereby failures are regarded as inevitable but may be made relatively non-damaging to the reactor.
- b. Reducing unit cost of production without increasing failure rate.
- c. Providing features that are compatible with more severe reactor operating conditions.

Thus, it may be stated that the present tests have contributed materially to our knowledge of the relationships between fuel element quality and irradiation behavior. A few of these new or revised concepts are discussed below. Some points may be considered definitely proved, others strongly supported, and still others merely indicative of a tendency.

(1) Decreasing the coolant flow by reduction of the annulus as much as 0.030-inch (0.030-inch oversize slug diameter) opposite the tube ribs results in overheating the upper portion of the element, in positions downstream of center, where the ambient coolant temperature has been raised by the heat evolved in the upstream regions of the tube. It may be postulated that operating at higher power levels would tend to move the position of beginning of this phenomenon upstream, with even more severe manifestations of its occurrence taking place in the down-stream regions. Certainly

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aggravation of the adverse consequences of operating at higher specific power with restricted annulus, as here exemplified in the case of the hot-pressed elements, may be expected.

The mechanism of this behavior can only be surmised from the data available; however, it furnishes a possible clue to the occurrence of hot-spot failures in standard production, and is thus worthy of further study on that account. The subject is discussed under the heading "Radiometallurgy Studies".

(2) Certain types of embedded particles cause accelerated pitting in immediately surrounding jacket areas, particularly where the particle lies in a zone of higher surface temperature (hot-spot zone).

Circumstantial evidence points strongly to fly-ash from the 300 Area power plant as a principal offender in this respect, although proof of its guilt has not been positively established. Attempts to identify the embedded material responsible for accelerated corrosion in the present test have been unsuccessful.

RADIOMETALLURGY STUDIES

Although underwater observations of the ~ 800 MWD/T discharged slugs, before cleaning did not reveal any serious condition of quality, re-examination after cleaning showed that more general damage had occurred in the hot-side zones than was at first apparent, and disclosed one slug (No. 151; PT 45A) which appeared to have suffered more than the usual amount. The cleaning agent used for defilming the slugs apparently had caused the calcareous scale to slough off, carrying with it the disintegrated aluminum grains which had been separated from the jacket body by intergranular corrosion. Thus the jacket surface was left rugged and gnarled in appearance. (Figures 4 and 5)

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This specimen was brought to the Radiometallurgy Laboratory in Building 327 for more detailed study. The entire hot-side zone was shown to be rather severely attacked. (Figures 5, 6, 7, and 8). In the vicinity of a group of embedded particles, especially severe corrosion of the jacket had occurred, reducing its thickness to about 0.002 inch (Figures 6, 9, and 10), and there was generally severe corrosion spread over the entire hot-side area. According to the weigh-loss data, (Figure 11), this particular specimen lost approximately 12-1/2 grams during irradiation. The cross sectional view shows that this loss tends to be concentrated over relatively small areas.

The microstructure of the jacket in the severely corroded zones (Figures 12 and 13) shows that the corrosion of the aluminum was intergranular in nature. The cleaning treatment has left a layer of partially detached grains at the surface, and this appearance, compared with that of the slug before and after cleaning, gives a clue to the probable mechanism by which the aluminum was stripped from the jacket surface. The order of events as deduced from this evidence together with known facts, is as follows:

The coolant water increases in temperature as it progresses through the tube, and this fact, coupled with the distribution of power generation in the tube charge, causes a marked rise in slug surface temperature in the entire downstream half of the tube, being especially pronounced in the vicinity of the position eight slug. At a temperature of about 100 C, the dissolved minerals in the coolant water begin to deposit on the slug surface, the rate of deposition being more rapid as surface temperature increases. This deposit, a form of "boiler scale", has a relatively low thermal conductivity and thus acts as a heat insulator, causing the temperature of the underlying aluminum to be increased. Eventually, the aluminum reaches a temperature⁽¹⁰⁾ at which it reacts with the moisture permeating the scale deposit, to produce intergranular corrosion, with partial detachment and sloughing off of the loosened grains into the scaly layer. The boiler scale mingles with the aluminum corrosion product and becomes impacted among

(10) Groot, C., and Wilson, R. E., Hot Spot Failures---, HW-41796.

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FIGURE 5

Appearance of the same slug shown in Figure 4, as viewed in the Radiometallurgy Lab hot cell. The group of embedded particles which first drew attention to this specimen is seen about $1/3$ of the length below the top of the slug. Note the general severe surface attack on the hot-side zone. Before cleaning, this region appeared only slightly damaged, principally around the embedded particles.

FIGURE 6

An enlarged view of the cluster of embedded particles and surrounding surface. The rosette-like formation at the right appeared to be undercut by the water, but the substrate uranium was thus far essentially undamaged.

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FIGURE 7

FIGURE 8

Views of surface at opposite end (Figure 7) and at middle (Figure 8) of same slug shown in Figures 4 and 5, as observed in Radio-metallurgy Lab. About 5-1/2 X.

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FIGURE 9

View of cross-section in transverse plane just below cluster of embedded particles. Jacket has been thinned by corrosion, especially at the extreme right.

FIGURE 10

Enlarged view of most severely attacked portion of jacket shown in Figure 9. Thinnest region measures ~ 0.002 inch.

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FIGURE 11

Weight loss vs position in tube, with calculated slug surface temperature for comparison.

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FIGURE 12

Micrograph of aluminum can wall, showing how intergranular corrosion has loosened and partially detached the outermost layer of aluminum grains. Overlying layers were removed by the H_2SO_4 - H_2CrO_4 cleaning solution. Embedded particles are grit from cut-off wheel not removed by polishing. 250X

- ← Burr from cutting
- ← Layer of grains loosened by intergranular corrosion
- ← Remains of Al can wall
- ← Nickel Layer
- ← Uranium Core

FIGURE 13

Micrograph of thinnest section of jacket wall. Note that nickel barrier layer is unaffected by the high temperature, or by aluminum corrosion going on in nearby region. Top tier of metal is a burr from cutting, not removed in polishing. 590X

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the aluminum grains, binding the mass together to form a low thermal conductivity layer on the surface. The effect of this layer is to increase the temperature of the rest of the slug, including the better-conducting portions of the surface. So the deposit spreads slowly. The temperature gradients may cause warping of the slug, thus further closing-off of the coolant annulus, with further increase in local temperature, eventually leading to accelerated intergranular corrosion or actual fusion of the aluminum. In case the thermal and stress gradients are so low that warping does not occur, the attack zone remains broad and the corrosive action is proportionately less severe.

The chemical cleaning agent used to remove the film from the jacket surface dissolves the calcareous binder and causes the detached grains to slough off, leaving the underlying sound metal exposed. Thus, an evaluation of the quality status of irradiated slugs based on their as-discharged appearance (without cleaning) is apt to be erroneous, since the depth to which intergranular corrosion has penetrated the jacket cannot be reliably determined from pre-cleaning observation.

It had been planned that pre- and post-irradiation weight measurements would be taken on all the hot-pressed slugs and their controls. This was done on the test pieces, but through some oversight the lead-dip control slugs missed the pre-irradiation weighing, so there was no point in weighing them afterward.

Weight-loss data obtained by weighing slugs before and after irradiation, on different types of balances, by different persons, under different environmental conditions do not give a reliable indication of the depth of penetration by corrosion; hence the residual quality of an irradiated slug in terms of its probable remaining reactor life cannot be adequately judged from weight-loss data. On the other hand, variations in gross corrosion effects are made strikingly evident by comparison of weight-loss data, so that such information is useful in comparing different types of

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jacketing material, different coolant compositions, etc., with respect to their general bearing on corrosion of fuel elements.

When the weight-loss figures for the three long-exposure columns of slugs in PT 45 A are plotted against their position in the tube, an interesting family of curves results. (Figure 11). Three features stand out in this chart:

- a. The sharp increase in general corrosion with relatively small increases in surface temperature.
- b. The essential equivalence of weight loss at the same tube position for the 600 and 800 MWD/T exposure slugs, except at position eight.
- c. The upstream displacement of peak weight-loss from peak slug surface temperature as calculated from operational data. (Furnished through courtesy of R. E. Hall.)

This composite chart illustrates several quality concepts which heretofore have not received much emphasis, nor wide recognition.

1. A fuel element whose quality is adequate in the upstream half of a tube may be far from adequate in the downstream half of the same tube. Hence valid quality comparisons between tubes of test slugs must be made on the basis of equivalent position in the tubes.
2. An outstanding weakness of the aluminum jacketed slug is its sensitivity to temperature; i. e., its sharp increase in general corrosion rate with relatively small increases in temperature beyond a definite threshold.
3. Fuel element surface areas which, due to any of several conditions, are caused to operate at temperatures above a threshold minimum, are subject to accelerated attack, at a rate increasing sharply with increasing temperature. Thus an upstream slug with areas of abnormally high surface temperature may deteriorate at a rate equal to or greater than that of a normally operating downstream slug.

4. There is no sharp distinction between the hot-spot failure and high-temperature general corrosion as exemplified in the downstream slugs of these production tests. The differences are merely in degree and in localization due to geometry.
5. The area of a fuel element on which a hot-spot develops is normally not a zone overlying a region of poor heat transfer in the bond. On the contrary, a good localized flow of heat from core to jacket is essential to the formation of the hot spot. However, impaired heat removal from other areas of the surface tends to raise the over-all core temperature so that areas of good conductivity become hotter than normal. Thus, reactor condition which result in the upper half of the water annulus operating at a considerably higher temperature than the lower half are especially conducive to the formation of hot-spots on the side of the fuel element opposite to the ribs.

Another interesting aspect of the study was furnished by one of the vacuum-canned slugs (# P 133, position 4, Tube C-3364, exposure approximately 800 MWD/T) which after irradiation gave a strongly positive indication of unbondedness on the underwater ultrasonic tester. This specimen was dissected for verification of the lack of bond, with the results illustrated in Figures 14, 15, 16, and 17.

Because of its proximity to the position of peak severity, this slug would be expected to show pronounced surface attack. The fair-sized areas of separated bond indicated by the ultrasonic tester (and verified by Radiometallurgical examination) logically should have increased the surface temperature of actively conducting areas, and rather severe localized corrosive attack of the jacket might have been anticipated. Actually, there was no obvious deterioration of quality, no significant corrosive attack; only a slight buildup of the boiler-scale deposit, which was largely removed in cleaning. The cross-section (Figure 14) shows how little the jacket wall thickness had been reduced.

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FIGURE 14

Cross-section through zone which gave strong indications of unbondedness on post-irradiation ultrasonic test instrument. Gaps between core and jacket are seen at locations numbered 1 and 6. See enlarged views of these zones. (Figures 15 and 16)

Aluminum Can

Al-Si Bonding
Layer

Gap

Uranium Core

FIGURE 15

Enlarged view of location 1. Note thinness of Al-Si bonding layer, and width of gap between core and jacket (internal tube)
90X

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Bonding Layer

Gap

Uranium

FIGURE 16

Enlarged view at location 6. Gap between jacket wall and uranium core is small, but unmistakable. This slug had successfully passed both Frost Test and Sonobond Test prior to irradiation. 90X

Bonding Layer

Compound Layer

Uranium Core

FIGURE 17

Enlarged view of location 3, about 120° removed from location 1. Note thickness of Al-Si layer and compound layer in comparison with Figure 15. This illustrates the principle that rate of compound layer formation is affected by the amount of Al-Si available for the uranium to react with. 90X

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Reasons for these anomalous effects can only be conjectured. It is possible that the slug operated with the broken bond for only a short period, or even that the separation occurred during or after discharge. On the other hand, it is possible that the heat transfer across the bonded zones is exceptionally good in this type of slug (in which the compound layer is thin and composed only of U, Al, and Si) so that the detrimental effect of discontinuities in the bond is somewhat alleviated. No valid conclusion can be drawn from this single observation regarding the relationship between unbonded areas and susceptibility to failure. Indeed, no facilities nor techniques now exist for determining the size of unbonded areas on irradiated slugs, and since it seems probable that the effect of unbondedness is a function of the size of the total unbonded area, no valid conclusions in this respect are apt to be forthcoming until suitable measuring facilities have been developed and put into service. One fact, however, seems abundantly clear: All other things being equal, a fuel element with excellent heat transfer properties affords a much better risk for reactor exposure than one with spotty heat transfer zones.

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