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TITLE

STATUS OF DEVELOPMENT WORK ON THE HOT DIE SIZE FUEL ELEMENT GROWTH PROBLEM

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STATUS OF DEVELOPMENT WORK

ON THE

HOT DIE SIZE FUEL ELEMENT GROWTH PROBLEM

by:

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November 5, 1964

MASTER

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INTRODUCTION

The hot die sizing (HDS) process is being developed as a replacement for the existing AlSi dip-brazing process. Internally and externally cooled tubular fuel elements are fabricated by passing a preheated core-component assembly through a die ring to bond the external surface. Currently, the assembly is passed over a die plug to bond the internal surface. The aluminum-nickel diffusion bond is formed by the application of pressure upon the preheated assembly while the aluminum cladding is formed or drawn around the electro-nickel plated core. The abrading action of aluminum sliding past the nickel surface enhances diffusion bonding by breaking the oxide films producing a clean reactive surface. The clean surface permits diffusion to proceed rapidly during the short time that the piece contacts the die and is above 350 C, below which there is no diffusion. End bonding is accomplished in a following step by applying heat and pressure to the end surfaces of the fuel element.

Post-irradiation measurements of the initial irradiation production test (PT-IP-546-A) after exposure to about 900 MWD/T revealed an unforeseen growth behavior of hot die sized fuel. Inner and outer diameters at the midsection of hot die sized fuel elements increased 0.006 inch and 0.008 inch, respectively, more than AlSi brazed control elements.⁽¹⁾ Subsequent metallurgical examination of irradiated fuel revealed no bond deterioration, grain boundary tearing, or change in core density. Unexpected growth of HDS fuel required above-normal forces to discharge the test columns from the reactor. For this reason, the second production test (PT-IP-616-A) was discharged below goal exposure. The second test also required above-normal discharge pressures, indicating fuel element growth. Post-irradiation measurements confirmed similar dimensional changes to those experienced in the initial test.

Because of the unexpected growth behavior of hot die size fuel elements during irradiation, it was necessary to re-evaluate the plans for hot die size irradiation testing and redirect the development effort. Tests were initiated to determine the cause of the growth, and plans were made to incorporate findings into subsequent irradiation tests. This report summarizes work done to determine the cause of the unexpected growth and the status of irradiation tests designed to measure improvements in the growth behavior of irradiated hot die size fuel.

SUMMARY

Ex-reactor tests designed to detect the cause of the unexpected growth behavior of hot die sized fuel elements indicate that both end bonding and core heat treatment could be contributors to the problem. There was some evidence of hot metal working and increased twinning in the uranium core of hot die sized fuel. However, metallurgical examination of irradiated fuel revealed no evidence of bond deterioration and grain boundary tearing or change in core density. X-ray diffraction studies did not reveal any detectable differences between HDS and AlSi brazed cores, except that the outside edge of HDS cores was made up of high-growth index material. This "skin effect" was attributed to temperature gradients in the core blanks during quenching at the uranium feed site. The larger hot die size cores are machined from the same core blanks as corresponding AlSi dip-braze cores which accounts for the more pronounced "skin effect."

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Three production tests either have been or are presently being irradiated to determine the effect of suspect process variables upon irradiation performance. The tests were designed to detect the effect of the following variables upon fuel element dimensional stability: (1) induction versus resistance heated end bonding methods, (2) end bonding pressure, (3) core dimension changes which influence "skin effect", and (4) core heat treatment.

DISCUSSION

Due to the unexpected growth behavior of hot die sized fuel elements during irradiation, a program to determine and eliminate the cause was initiated. The program consisted of studies in the following areas:

- (1) Metallurgical examination of the uranium core.
- (2) Measurement of core dimensional changes produced by the various steps in the process.
- (3) X-ray diffraction studies.
- (4) Determination of core dimensional changes in hot die sized fuel induced by thermal cycling.
- (5) Measurement of the difference in coefficient of thermal expansion of AlSi dip brazed and hot die size fuel elements. (The coefficient of thermal expansion for uranium has a relationship to growth index.)
- (6) Continued irradiation to gain additional reactor experience with hot die sized fuel elements.

A number of the above mentioned studies were carried out concurrently. Each item will be discussed in the order given under separate headings.

Metallurgical Examination of Uranium Cores

Metallurgical examination of uranium cores clad by the HDS and AlSi dip-brazing process revealed a slight difference in the structure of HDS clad cores. There was evidence of recrystallization produced by hot working and increased twinning the HDS core.(2)

Examination of irradiated HDS fuel from the first test (PT-IP-546-A) in the Radio-metallurgy facility showed no fuel deterioration as a result of irradiation. There was no evidence of uranium grain boundary tearing, no change in core density, or no evidence of bond deterioration.

Core Dimensional Changes During Processing

Cores from a single ingot were plated with a double thickness of nickel plate (~0.0018 inch) for use in a test designed to determine the effect of the various hot die sizing process steps upon core dimensions. A double thickness nickel

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plate was used to insure complete core coverage to prevent contamination of the furnace and work area with uranium oxide. The plated fuel cores were measured and processed through the following steps or modifications of steps:

- (1) As-plated cores (controls)*
- (2) Sizing*
- (3) End bonding preheat
- (4) Resistance heated end bonding - water quench*
- (5) Resistance heated end bonding - air quench
- (6) Induction heated end bonding

* Normal process steps. Other items listed are either a part of a process step, a modification of a process step, or a different method.

After processing, the clad pieces were measured and then dejacketed to remove the 8001 aluminum alloy cladding by the standard core recovery process. The recovered cores were then measured again. Average inner and outer diameter changes and warp for both the aluminum clad fuel elements and nickel plated core are shown in Table 1. It will be noted that the outer diameter of fuel elements and bare cores end bonded by the resistance heated press and water quenched (the standard process at that time) both had the greatest change. The induction heated end bond press produced cores having only a slight change. Core internal diameters increased for all steps of the process, but were affected most by end bonding, regardless of the process used. The resistance heated end bonded and air quenched cores had the greatest change. There did not seem to be any correlation between the internal bare core and internal clad dimensional changes. Resistance heated end bonding produced the greatest warp in both the bare cores and clad fuel. Changes in hot die size core diameters and warp are graphically illustrated in Figure 1.

From results of work with these dimensional changes in uranium cores clad by the hot die sizing process, it was concluded that the end bonding step could be a contributor to the unexpected growth behavior of HDS fuel during irradiation. For this reason, work on the new induction heated end bonding press was accelerated.

Processed cores for this test were submitted to the UT-2 grain size test. The differences between voltage readout for the six different conditions were found to be statistically significant. Average grain size values obtained are listed below.

<u>Core Treatment</u>	<u>Average UT-2 Voltage</u>
A. Nickel Plated Cores (Control)	2.42
B. Sized Cores	2.60
C. Preheated for End Bonding	2.70
D. End Bonded-Standard Water Quenched (Resistance Heated)	2.29

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TABLE 1

SUMMARY OF AVERAGE CHANGES IN CORE AND FUEL ELEMENT
DIMENSION DUE TO VARIOUS STEPS IN THE HOT DIE SIZING PROCESS

Core Treatment	Diameter and Warp Charges in Mils					
	ΔOD		ΔID		D_4 (Warp) (Double Throw)	
	Bare	Clad	Bare	Clad	Bare	Clad
A. Nickel plated cores control	0	--(1)	0	--(1)	0	--(1)
B. Sized cores(2)	+0.22	0	+0.91	0	+0.13	-0.12
C. Preheated for end bonding	-0.21	-0.50	+0.86	+0.04	-0.16	0
D. End bonded - standard water quench (resistance heated)	-2.92	-3.48	+1.19	-0.13	+2.27	+0.88
E. End bonded - air quench (resistance heated)	-0.52	-0.50	+1.76	-0.42	+2.13	+1.38
F. Induction heat end bond	+0.07	--(3)	+1.43	--(3)	+0.43	--(3)

(1) Nickel plated cores - were not jacketed or processed.

(2) Served as controls for clad fuel measurements.

(3) Unavailable for measurement.

FIGURE 1
IDS Process Core Dimension Changes

<u>Core Treatment</u>	<u>Average UT-2 Voltage</u>
E. End Bonded-Air Quench (Resistance Heated)	2.41
F. Induction Heated End Bond	2.58

It is concluded that the UT-2 tester may be a tool to measure changes induced in HDS cores by processing. It is known that the tester is sensitive to other changes in addition to grain size changes. In this case, changes in grain boundary structure could have produced the observed voltage differences. Use of the UT-2 test for this type of test will require additional development and testing.

X-Ray Diffraction Studies

X-ray diffraction studies of uranium cores taken from close positions in the original rolled rod and clad by hot die sizing and by AlSi brazing revealed different growth indices close to the outer surfaces of the cores. The differences were believed to have been caused by heat treatment effects on the core blanks. Hot die size cores are 0.026 inch larger in diameter than corresponding AlSi cores. Because of this difference in size, less high growth index material is removed in finished core machining of HDS cores. Figures 2 and 3 show plots of growth indices calculated from X-ray diffraction data taken from cores clad by both processes. Measurements taken on both core types are plotted individually, but they are not considered different, except in the thin region near the outside surface. A single curve has been drawn through the data points for both core types. Note that the growth index in the region near the surface of the AlSi core is changing rapidly. A data point on the HDS core which is still closer to the original slug blank surface has still a greater change as can be most readily seen in Figure 2.

Dimensional Changes Induced by Thermal Cycling

Hot die sized fuel elements were thermal cycled to determine the effect of rapid changes in temperature upon fuel dimensions and to serve as a guide in planning additional thermal cycle tests. No changes were detected in dimensions of pieces cycled up to 50 times by heating to 350 C and quenching to 10 C; however, marked changes were observed in pieces cycled up to 50 times to 450 C and quenching to 10 C. Average lengths increased 0.0103 inch and the internal diameters increased 0.0041 to 0.0055 inch at the fuel ends. As can be noted in Figure 4, the fuel took on an hour glass configuration. Outside diameter changes were slight, but tended toward a similar hour glass effect.

In an effort to confirm the above findings, an additional thermal cycling test was run. This test was also an attempt to establish a relationship between thermal cycling and in-reactor experience by using fuel elements matched with those undergoing irradiation. Fuel elements for this test matched pieces charged for production test (IP-655-A) which was designed to measure differences in induction and resistance heated end bonding processes.⁽³⁾ Eight pieces each of AlSi brazed, induction heated end bonded HDS, and resistance heated end bonded HDS fuel elements were cycled 30 times between 450 C and 10 C. Due to a limited capacity in the muffle furnace, the

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FIGURE 2

Radial Growth Indices

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FIGURE 3
Longitudinal Growth Indices

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FIGURE 4
HDS Fuel Dimension Changes Due to Thermal Cycling

test pieces were divided with four pieces of each type and cycled in two groups. Results of this test were inconclusive in that there was a difference between the two groups cycled. It is theorized that thermal cycling may still be a means of predicting in-reactor fuel performance; however, much tighter control on the heating and quenching environments will be required. Fuel elements are being prepared to set up tighter temperature control on pieces during heating and quenching for future thermocycling tests.

Measurement of HDS and AlSi Core Coefficient of Thermal Expansion

Matched hot die sized and AlSi dip brazed cores were processed and prepared for measurement of the core thermal expansion coefficients. Uranium growth indices increase and decrease as the thermal expansion coefficient decrease and increase, respectively.

Data obtained by measuring three samples taken from an HDS and an AlSi brazed core show a very slight difference in the thermal expansion coefficients.⁽⁴⁾ The average HDS thermal expansion coefficient is slightly less than that of the AlSi dip-brazed core, but it is not considered to be significantly different. Results of the thermal expansion measurements shown in Table 2 suggest that the HDS core would grow slightly more than an AlSi dip-brazed piece during irradiation.

Thermal expansion measurements were taken by Hanford Laboratories personnel. Measurements were taken on three 2.000 inch by 0.375 inch diameter plugs machined from the center of an AlSi dip brazed and hot die sized fuel element. As an effort towards maintaining core uniformity, cores machined from adjacent positions in the parent rod stock were selected for testing. Centers of the 0.375 inch diameter plugs were located on circles having equal diameters to minimize the possible difference in uranium structure due to quenching at the feed site.

Continued Irradiation

Prior to discharge of the first and second hot die size fuel element production tests, a third production test consisting of 24 charges containing HDS and AlSi brazed fuel was assembled for charging under Production Test IP-630-A. However, after the unexpected growth of HDS fuel during irradiation was discovered, the test was changed and reduced to 10 charges⁽⁵⁾ for charging under Supplement A to Production Test IP-546-A. The 10 columns consisted of five charges of HDS fuel and five charges of alternating HDS and AlSi brazed fuel. The purpose of this test was to obtain data on the relationship of the coolant temperature distribution and fuel element behavior.⁽⁶⁾ As an added precaution against sticking in reactor process tubes and to allow for expected growth during irradiation, the self-support height of fuel elements for this test was reduced by 0.005 inch. Revised and standard self-support projection height dimensions for the self-support C-size fuel element are compared below.

	<u>Revised Dimension</u>	<u>Standard Dimension</u>
Support Height (Minimum)	0.077 in.	0.082 in.
Effective O.D. (Maximum)	1.656 in.	1.666 in.

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TABLE 2

THERMAL EXPANSION COEFFICIENTS* FOR
ALSi DIP-BRAZED AND HOT DIE SIZE URANIUM FUEL ELEMENT CORES

<u>Process</u>	<u>Sample No.</u>	<u>Heating</u>			<u>Cooling</u>		
		<u>300 C</u>	<u>500 C</u>	<u>RT-600**</u>	<u>300 C</u>	<u>500 C</u>	<u>RT-600**</u>
ALSi	3A-1	18.00	21.15	17.25	17.25	25.00	18.10
	3A-2	18.20	19.40	17.05	17.55	20.50	17.65
	3A-3	18.35	23.45	18.70	18.35	22.40	18.95
	Average	18.18	21.33	17.67	17.72	22.63	18.23
HDS	3H-1	17.15	19.80	17.25	17.95	26.60	18.52
	3H-2	16.90	20.00	16.98	16.95	18.90	16.72
	3H-3	18.05	21.05	17.25	18.00	21.30	17.92
	Average	17.37	20.28	17.16	17.63	22.27	17.72

* in./in./°C x 10⁻⁶

** Average values from room temperature to 600 C.

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The ten columns for this test were charged February 27, 1964, and discharged April 28, 1964, after irradiating to average exposure of about 540 MWD/T. Nine of the ten columns required above normal discharging pressure.

As a result of previously discussed work, and the acquisition of new end bonding equipment, Production Test IP-665-A was prepared to compare differences in growth behavior between the induction heated and resistance heated end bonding processes.⁽³⁾ Twelve columns containing induction heated end bonded HDS fuel, resistance heated end bonded HDS fuel, and AlSi dip-brazed fuel were assembled. Cores for the three fuel types were taken from the same ingots produced at the uranium feed site to minimize core induced variation during irradiation. Eleven of the test columns were charged in C Reactor April 29, 1964, and discharged September 1, 1964, after irradiation to about 800 MWD/T. No unusual pressures were required for discharging. Hot die size fuel elements for this test experienced the same growth behavior as in the initial tests. Induction heated end bonded fuel had a slightly less increase in growth, indicating that the end bonding process contributes to the unexpected growth of HDS fuel. Differences in internal diameter changes for the two end bonding types were slight. As in the initial production test (IP-546-A), warp and the incidence of double bend profile (52 per cent) was the same for both the HDS and AlSi brazed test pieces. Weight loss for the test pieces was the same, indicating no difference in corrosion rate. Changes in dimensions and weights for this test are summarized in Table 3.

TABLE 3

Dimensional Changes of Induction Versus Resistance
Heated End Bonded Hot Die Size Fuel Elements During Irradiation
(PT-IP-655-A)

	<u>Resistance End Bond</u>	<u>Induction End Bond</u>	<u>AlSi Brazed</u>
O.D.1	7.3 mils	6.2 mils	3.0 mils
O.D.2	14.5 "	12.5 "	5.8 "
O.D.3	12.9 "	11.6 "	6.5 "
Warp	2.4 "	2.5 "	2.6 "
I.D.1	13.9 "	13.3 "	3.0 "
I.D.2	12.3 "	12.3 "	3.0 "
I.D.3	12.5 "	11.7 "	2.8 "
Weight Loss	1.4 gm	1.2 gm	1.2 gm

As previously mentioned, on the basis of ex-reactor tests, the expected difference between the initial induction heated end bonding and the former resistance heated end bonding was expected to be only slight, but an improvement. With the gaining of experience and improved techniques, induction end bonding has been used to apply heat at the ends more rapidly while maintaining a lower temperature at the fuel midsection.

Because of the length of time involved in material procurement, fabrication, irradiation, post-irradiation measurement, and data analysis, additional production tests were prepared for irradiation testing. Fuel elements were fabricated to determine the effect of process parameters and core heat treatment upon irradiation behavior of HDS fuel.

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Twenty-four columns of HDS and AlSi brazed control fuel elements were prepared for Production Test IP-684-A to evaluate core heat treating "skin effect" and pressure variation during end bonding upon irradiation performance.⁽⁷⁾ As previously mentioned, HDS cores were machined from the same rod stock as standard cores. Because of the 0.026 inch difference in diameter, there was a difference in measured growth index as shown in Figures 2 and 3. Since this difference was apparent, HDS cores were machined down to the standard AlSi core external diameter to remove the thin skin of high growth index material. Thick wall aluminum cans were used to compensate for the reduction in core size. Standard size and machined cores were both subjected to the variation in end bonding pressure for this test. The two pressures used were $3\frac{3}{4}$ and $4\frac{1}{4}$ T/in.² applied to the end of the piece. End bonding conditions (time, temperature, and power settings) were changed for this test to apply more heat to the end section while reducing the amount conducted to the midsection. (See Table 4 for a summary of end bonding process conditions used for induction heated fuel elements discussed in this report.) The 24 columns prepared for the parameters test were charged in C Reactor July 16, 1964, and are scheduled to be irradiated to a goal exposure of 800 MWD/T. Goal exposure is expected during November 1964.

Eighteen columns of fuel elements were prepared to determine the effect of heat treatment upon HDS fuel during July and August of 1964.⁽⁸⁾ Oil and water quenched cores for this test were taken from alternate positions in the core and rod stock. Each of the two quench-type cores were divided into thirds to further vary the heat treatment by stress relieving. Stress relieving consisted of alpha annealing and an AlSi dip-braze pretreatment. The third group consisted of as-received oil or water-quenched cores. The test columns were charged in C Reactor September 1, 1964 as authorized by Production Test IP-708-A and are scheduled to be irradiated to a goal exposure of 800 MWD/T.⁽⁹⁾ As with the previous test, additional improvements in the operation of the induction heated end bond press permitted faster heating of the fuel element ends, thus reducing over-all heating time. End bonding conditions for the tests using the induction heated end bonds are summarized in Table 4.

FUTURE PLANS

Future plans regarding the unexpected growth problem associated with hot die size fuel elements depend upon results of the test material now undergoing irradiation. However, in the event that none of the tests presently being irradiated are successful in reducing the growth experienced, alternate plans for testing and irradiating increased quantities of fuel have been made. They include (1) reducing the core and finished fuel diameter both by about 0.005 inch to permit the fuel element to grow during irradiation, and (2) to procure alloyed uranium for a core optimization test to determine the effect of various additives upon irradiation performance.

Reducing the outside core and finished fuel diameters would be relatively simple in that the new size can be obtained by merely reducing the core diameter and changing sizing and end bonding die dimensions. A corresponding change in the inside diameter may also be necessary and would have to be calculated.

Procurement of alloyed uranium material would require additional time and coordination between the feed site and Hanford. Presently varying amounts of iron, silicon, and aluminum are being considered as additives to hot die size uranium

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TABLE 4

COMPARISON OF INDUCTION HEATED END BONDING PRESS CONDITIONS FOR PRODUCTION TESTS

	IP-665-A Induction vs. Resistance* End Bonding	IP-677-A Tubing Clad	IP-684-A Parameters Test - "Skin Effect" and End Bond Pressure	IP-708-A Core Quench and Stress Relieving
Pressure	4.0 T/in. ²	3.6 T/in. ²	Two pressures used: Low $3\frac{3}{4}$ T/in. ² High $4\frac{1}{4}$ T/in. ²	4 T/in. ²
Head Temperature	775 C	775 C	750 C	725 C
Head Alloy	Stainless Steel No. 416	Stainless Steel No. 416	Stainless Steel No. 416	Inconel-X
Time	Press Time Low pressure - 3 min. 0 sec. High pressure - 1 min. 10 sec. Total 4 min. 10 sec.	Press Time Low pressure - 3 min. 10 sec. High pressure - 2 min. 0 sec. Total 5 min. 10 sec.	3 min. 10 sec.	2 min. 45 sec.

* Resistance heated end-bond press conditions for comparison purposes.

Fuel-die assembly preheat in 680 C resistance furnace.	5 min. 45 sec.
End bonding press time.	4 min. 30 sec.
Total heating time.	10 min. 15 sec.

Pressure	4 T/in. ²
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Head Temperature	655 C
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cores to aid in controlling growth. These additives are known to influence the growth of uranium during irradiation. A test to fabricate, irradiate, and evaluate three levels of each of the three proposed additives in various combinations has been designed and is ready for use in the event it is required.(10)

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