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INTERIM REPORT
HIGH PRESSURE, LOW TEMPERATURE
END BONDING OF HDS FUEL

G. M. Schweikhardt

DECLASSIFIED
INTERIM REPORT
HIGH PRESSURE, LOW TEMPERATURE END BONDING OF HDS FUEL

by:

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January 10, 1967

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39-50. Extras
I. INTRODUCTION

A solid-state diffusion bond is produced at the end bonding step of the Hot-Die-Size (HDS) process as the aluminum cladding is placed in intimate contact with the nickel-plated uranium core for a finite period of time at an elevated temperature. The combination of these required parameters of time, temperature, and intimate contact (pressure) may be varied within certain limits and still produce a quality diffusion bond. For example, two highly polished metal samples may be diffusion bonded at room temperature under moderate pressure if sufficient time is allowed. At the other extreme, a diffusion bond is formed in a fraction of a second at elevated temperatures and pressures (dynamic loading) in the sizing operation of the HDS process.

Diffusion bonds are formed on HDS fuel elements in two process steps. First the fuel is sized through and over an external and internal die, respectively, to form the lateral bond. Secondly, the ends are bonded by placing containment dies over the ends of the fuel and subjecting this assembly to an end loading pressure at an elevated temperature. This end bonding process is a static loading process as opposed to the dynamic loading encountered in sizing. Therefore, the time required to form the diffusion bond on the ends during the end-bonding process is considerably longer than that required to bond the lateral surfaces at sizing. The objective of the testing being reported in this document, therefore, was to determine the feasibility of reducing the end bonding cycle time by one-half through developing the proper combination of time, temperature, and pressure without a loss of fuel quality. This test will cover the data developed from the initial work with high-pressure and low-temperature end bonding. This was a statistical test and was designed to demonstrate the feasibility of such a process and to establish the optimum operating parameters.

II. SUMMARY

Through nondestructive and destructive testing, fuels end bonded at the higher pressure proved to be of equal quality to those produced under standard conditions. Bond testers indicated no significant difference between test and control fuels. This was verified with bond strengths that were equivalent to those of control fuels. Metallographic data also confirmed the formation of a thinner, apparently more uniform, bond on the test fuels than on the controls. X-ray data that defined the longitudinal growth showed no difference between test and control fuels.

III. DISCUSSION

The objective of the testing covered in this document was to reduce the end-bonding cycle time (increase throughput) on the four-station prototype end bonder (see Figure 1). However, before discussing the test results, it is necessary to understand the process cycle sequence. As can be seen from Figure 2, the cycle contains several overlapping functions at the four operating stations. The end bonder is set up so that stations 1 and 3 operate simultaneously and 2 and 4 operate simultaneously.
Figure 1

FOUR STATION PROTOTYPE END BONDER
CURRENT CYCLE

PRE HEAT → HEAT TIME → HOLD → LOAD UNLOAD → PRE HEAT → HEAT TIME

STATION 1 & 3

TEST CYCLE

PRE HEAT → HEAT TIME → HOLD → LOAD UNLOAD → PRE HEAT → HEAT TIME

STATION 1 & 3

PRESSURE APPLIED

INDUCTION HEAT APPLIED

FIGURE 2

END BOND CYCLE SEQUENCE FOR FOUR UNIT STATION
A. Cycle Sequence

There are four functions performed in a cycle for each of the two sets of stations. First, the ram heads (see Figures 2 and 3) are "Pre-Heated" to a pre-set control temperature. As soon as this temperature is attained, the heads advance to apply an end loading pressure to the fuel assembly. When the pressure is applied, heat from the ram head is absorbed by the fuel-die assembly. This loss of heat in the ram head causes the temperature to drop below the control point, which in turn reappplies the induction heating power. The length of time that this induction power is applied is known as "Heat Time." At the end of this "Heat Time," the induction power is switched to the "Pre-Heat" stage of the cycle on stations 2 and 4. Station 1 and 3, however, continue under pressure for a period of time designated as "Hold." This "Hold" period is necessary to allow time for the diffusion bond to form, now that the ends of the fuel assembly have been heated to bonding temperature. After the "Hold" period, pressure is released from the fuel assembly and the end-bonded fuel is unloaded and water quenched. A new fuel assembly is then loaded into place for a repeat of this cycle.

While stations 1 and 3 are going through the "Hold" and "Unload-Load" portions of the cycle, stations 2 and 4 will have completed the "Pre-Heat" and "Heat Time" functions. Therefore, the induction power is switched back to stations 1 and 3 to start a new cycle while stations 2 and 4 continue on to the "Hold" and "Unload-Load" portion of that cycle. This sequence is repeated between the two sets of stations during operation of the four-station end bonder.

It is evident from Figure 2 that the throughput cycle is determined by the sum of the "Pre-Heat" and "Heat Time," which must be equal to or greater than the sum of "Hold" and "Unload-Load." In the present process, this total is two minutes ("Pre-Heat" 25 seconds - "Heat Time" 95 seconds). Therefore, the "effective" throughput rate is 60 fuels per hour (two every 120 seconds). The remainder of the cycle is composed of 70 seconds for "Hold" and 50 seconds for "Unload-Load." Unloading and loading do not require the full 50 seconds; however, this time is available because the induction power may not be switched to the loaded units to start another cycle until the opposite cycle "Pre-Heat" plus "Heat Time" has elapsed.

Induction power is applied to the ram heads on the four-station prototype end bonder by two 10 kilocycle (kc), 20 kilowatt (kw) induction heating units. Each unit services two stations of the four-station end bonder. During the "Pre-Heat" portion of the standard cycle, 20 kw is applied to heat the two sets of ram heads. However, during the subsequent "Heat Time" portion of the cycle, the power is dropped to 15 kw. (Carry-over from use of the AlSi wafer between the aluminum cap and the end of nickel-plated uranium fuel core. If 20 kw were used, the AlSi wafer would penetrate through the external cladding.)
Equipment requirements for an HDS production facility are based upon original assumptions of a throughput rate of 120 fuels per hour. Capability under the existing process is only 60 per hour. Therefore, the sum of the "Pre-Heat" and "Heat Time" must be reduced by one-half (to 60 seconds). In order to accomplish this reduction, it would be necessary to heat the fuel assembly more rapidly to the bonding temperature and/or reduce the threshold bonding temperature by some means. The simplest change would be to increase the induction power from 15 kw to 20 kw during the "Heat Time" portion of the cycle. However, everything else being equal, this increase in heating rate would, in itself, be insufficient to produce a quality diffusion bond at the reduced time.

Since time, temperature, and pressure are the only process parameters affecting the formation of the diffusion bond, and since the cycle time is somewhat fixed by the scope of the test and the heating rate fixed by the equipment capability, pressure is the only parameter left to be tested. Detailed laboratory investigations\(^2\) indicate that increased pressure (2 to 11 tons/in.\(^2\)) upon the Ni-Al diffusion couple results in a three-to-one increase in the resultant bond strength when the bonding temperature is held constant. At the same time, increased pressure reduces the degree of penetration of the intermetallic formation at the bonding interface of the Ni-Al couple. These seemingly incompatible phenomena can be explained by the fact that the bond is weakened as the Ni-Al intermetals become thicker (Ni\(_2\)Al\(_3\) formation). Therefore, in the end bonding of HDS-fuels, it is desirable to hold Ni-Al intermetallic formation to a minimum as long as the diffusion bond is continuous. Bonding temperature requirements are also reduced as the pressure is increased on the Ni-Al diffusion couple.\(^2\)\(^3\) Therefore, at increased pressure, the temperature (time) of end bonding HDS fuels may be reduced to produce a Ni-Al diffusion bond of equal strength currently produced on the standard fuel.\(^1\) The U-Ni diffusion couple behaves differently than the Ni-Al couple when subjected to increased pressures. That is, the intermetallic formation is greater the higher the loading pressure. However, in this diffusion system, the compounds formed are not as brittle as the Ni\(_2\)Al\(_3\) system.

In the HDS process, standard end bonding procedures\(^1\) will produce a heavy NiAl\(_2\) compound layer and occasionally the brittle Ni\(_2\)Al\(_3\) layer at the bonding interface of the base end. On the other hand, the Ni-U diffusion system produces a very thin compound layer. Increased pressure, therefore, should not harm the bond, but should improve it on the base end at the shorter high-pressure end-bonding cycle. This increased pressure should also lower the threshold bonding temperature. Developing the proper combination of pressure and temperature should result in a fuel of equivalent fuel quality as the current semi-production HDS fuels. With these data as the background for the shorter end-bond cycle, the testing parameters were established to be 1) increased induction power and 2) increased pressure.
IV. **TEST PROCEDURE**

Two test procedures were used in the development of the high-pressure, low-temperature end-bonding cycle: (1) Initial testing was performed to demonstrate the feasibility of this high-pressure cycle. (2) With the results of this initial work, a statistical test was designed to optimize these processing parameters. Preliminary testing of the high-pressure end bonding concept was conducted on the 3 kc, 50 kw induction-heated development end bonding press. Because of the fact that the cycle time was already established by the scope of the test ("Pre-Heat" plus "Heat Time" not to exceed 60 seconds), the end loading pressure was arbitrarily raised to six tons per square inch (tsi) in an attempt to lower the threshold bonding temperature. (Twenty kw used in this test to duplicate capability of four-station prototype unit.) The first 10 fuels end bonded at these parameters showed signs of quality bonding. (Determined by the somewhat subjective "chisel" test. Degree of effort to remove the cap is used as indication of the quality of the bond.) With this basic feasibility established, the "Heat Time" and "Hold Time" were then varied over a range of 35 to 60 and 60 to 90 seconds, respectively. Based upon the results of this testing of time and pressure parameters, a more detailed test was designed for the four-station, 10 kc, 40 kw prototype end bonder. This test was designed to not only confirm the feasibility of this process, but to optimize the processing parameters of time, temperature, and pressure.

Timing sequence used in the statistical test was as follows:

<table>
<thead>
<tr>
<th>Test Cell</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Time (Seconds)</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Pre-Heat (Seconds)</td>
<td>25</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Hold Time (Seconds)</td>
<td>50</td>
<td>55</td>
<td>65</td>
</tr>
</tbody>
</table>

Pre-Heat Time on test cell one was increased to 25 seconds to allow sufficient time for the ram heads to recover to control temperature. Hold Time was increased as the Heat Time was increased to fully utilize available time under pressure. (Time allowed for load and unload was held constant--see Figure 2.) The above outlined test design was then repeated for end loading pressures of 4, 5, and 6 tons/in.$^2$ (tsi) of cross-sectional area on the end of the fuel.

<table>
<thead>
<tr>
<th>Test Condition No.</th>
<th>Heat Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
</tr>
</tbody>
</table>

During the test, the induction power was held constant at 20 kw for both Pre-Heat and Heat Time. Sample size at each test condition was set at 15
fuel, with the C3AN HDS fuel model being employed. Data generated on this fuel model may then be translated directly to other standard "8-inch" long models. Overbore (C6AN) and enriched fuel models, however, will require a replicate of this test. These data shall be reported as a supplement to this document.

V. TEST RESULTS

A. Initial Testing

Included in this section shall be the test results of both the preliminary testing on the 3 kc, 50 kw induction-heating development unit and the 10 kc, 40 kw, four-station prototype end bonder. Test results from the initial testing on the 3 kc development end bonder are included here only as a matter of record to indicate that this type of end bonding is feasible on this development unit. Figures 4, 5, and 6 include the metallographic and x-ray diffraction data gathered on this limited 3 kc end bonder test. Note the thinner Ni-Al diffusion compound on the high-pressure sample (45 second Heat Time and 50 second Hold). This reduction eliminates the more brittle Ni$_2$Al$_3$ compound occasionally found on the base end of standard fuels. Bond strengths, however, were not adversely affected by this reduced diffusion thickness.

<table>
<thead>
<tr>
<th>Test Fuel</th>
<th>Control Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap End</td>
<td>458</td>
</tr>
<tr>
<td>Can-Can Closure</td>
<td>1,100</td>
</tr>
<tr>
<td>Can Lateral</td>
<td>585</td>
</tr>
</tbody>
</table>

Longitudinal growth indices established by x-ray diffraction indicate that only minor variations are evident in the two samples (see Figures 5 and 6).

B. Four-Station Prototype Testing

1. Temperature Measurements

The remainder of the test result data shall be for the four-station prototype end bonder using the statistical test design. During fabrication of the fuel elements on the four-station end bonder, temperature measurements were taken on the O.D. cladding adjacent to the die cup. The averages for each test condition are outlined below: (also see Appendix A)
COMPARISON OF BASE END BONDS BETWEEN STANDARD AND HIGH-PRESSURE HDS FUELS PRODUCED WITH 3KC INDUCTION UNIT
GROWTH INDEX FOR STANDARD CYCLE END BOND

FIGURE 6

UNCLASSIFIED

CONTROL SAMPLE 3 KC INDUCTION UNIT

CENTER

CAP

BASE

NEGATIVE

POSITIVE

G-2 GROWTH INDEX (LONGITUDINAL)

UNCLASSIFIED
Table II

Cladding Temperature (1-1/4 inch from ends)

<table>
<thead>
<tr>
<th>Pressure (tsi)</th>
<th>Heat Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>212</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
</tr>
<tr>
<td>6</td>
<td>249</td>
</tr>
</tbody>
</table>

These cladding temperatures are considerably lower than those encountered on the standard cycle. For example, at 30 seconds Heat Time, cladding temperature was 180 to 200°C below standard, while at the 50 second Heat Time temperature is 110 to 130°C below standard.

It is interesting to note that a plot of these cladding temperatures reveals a different heating rate at 4 tsi than observed at the 5 and 6 tsi test condition (see Figure 7). All three, however, reach the same temperature after 50 seconds Heat Time. This would indicate that at 5 tsi and higher, heat transfer from the pre-heated ram heads is a maximum, thus indicating intimate contact between the uranium core and aluminum cladding at the start of the cycle. At the 4 tsi level, however, the initial heating rate (heat from ram heads) is less than optimum, indicating that the gap between core and cladding that is produced at sizing is not eliminated during the first portion of the cycle. On the other hand, as the fuel assembly is heated at the 4 tsi level, the induction field is concentrated in the relatively cool workpiece rather than in the hotter ram head. Thus at 50 seconds Heat Time, the final cladding temperature near the die cup is virtually the same as that observed at 5 and 6 tsi. Page 2 of Appendix E shows the effect of this reduced heating rate (cladding temperature) at the center of the fuel. (Hardness is a relative measure of temperature.)

Temperature measurements at the uranium-aluminum end interface were also recorded during fabrication. At 50 seconds Heat Time, the end interface temperature was an average of 410°C as opposed to 570°C on standard fuel (at 40 seconds Heat Time, innerface temperature was average of 375°C). It is only because of this reduced temperature that the end loading pressure may be increased to the 6 tsi level without danger of uranium metal upset (see Section V-7, Page 31).

2. Weld Inspect

Following fabrication, these fuels were subjected to both nondestructive and destructive tests to not only compare the quality between test conditions, but to compare them with fuels produced on the standard cycle (controls). Nondestructive testing included weld inspection and the use of various bond testers. During weld inspection, there were no weld defects such as pinholes, B1C, etc., detected, even though some were anticipated at the lower time and pressure test.
**FIGURE 7**

**FUEL CLAD HEATING RATES**

- ○ - 4 TSI
- △ - 5 TSI
- □ - 6 TSI

HEAT TIME - SECONDS
conditions. Thus the integrity of the closure produced on the high-pressure test fuels was at least equal to that produced on the control fuels.

3. Bond Testers

All test fuels were subjected to the UT-14 end bond test, UE-1 lateral bond test, and the UT-16 cap-to-clad closure tester. On the UT-14 tester, two rejectable non-bond areas were located on the cap end with one on the base end. The UE-1 tester located one internal non-bonded area that was larger than acceptable on the test fuels. The UT-16 tester passed all test fuels as having an acceptable cap-to-can closure. All of these rejects were scattered throughout the test and therefore are not correlated to any particular set of parameters. (4)

4. Metallography

A sample of two fuels from each test condition was submitted to the metallography laboratory for visual examination and nickel plate and diffusion bonding thickness measurements. Visual examination indicated the presence of diffusion bonding on fuels produced at both ends of the test spectrum (see Figure 8). However, those on the lower end of the time and pressure cycle indicated some non-bonding near the cap-can-core junction. The relatively heavy diffusion compound observed on the base end of standard fuels was markedly reduced on the high-pressure test fuels (see Figure 9). The diffusion layer on both the cap and base end of the high-pressure test pieces was quite uniform.

Diffusion thickness measurements taken on the base end of control fuels were considerably thicker than those recorded for the test fuels (see Appendix B). Diffusion thicknesses were measured on two fuel elements from each test condition at several locations on the base end, one inch from the base, the cap end, and one inch from the cap. All variations observed on the test samples were found to be random with neither time nor pressure being significant variables in the experimental range studied. (7)

Metallographic examination included x-ray diffraction studies to determine the G2 longitudinal growth index. This growth index was measured on six of the test fuels, one fuel element from each of the test conditions, excluding those at 4 tsi pressure. Since the measurements were made at several locations on the fuel element, four variables are defined:

**Measurement Locations:**

a. Fuel element radius at .30, .40, .50, .60 inches from I.D.

b. Samples taken at center, one inch from cap end, and one-half inch from cap end.
Figure 8

DIFFUSION THICKNESS COMPARISON WITHIN TEST PARAMETERS
Figure 9

DIFFUSION THICKNESS COMPARISON

STANDARD vs HIGH PRESSURE HDS FUEL
Test Conditions:
c. Pressure (5, 6 tsi)
d. Time (30, 40, 50 seconds)

Of these variables, only the first was significant. Plots of the various growth indices indicate little consistency in the behavior of the G2 index with the exception of its relationship to the fuel radius (see Appendix C). This is indicative of a fairly large random error component which makes it difficult to detect effects of variables unless they are relatively large. The radius effect averaged over the other three variables is shown in Figure 10. The continuous band depicts the 95 percent confident region within which the true average curve will lie. Any single reading will be expected to lie within the broader band indicated by the vertical line at the right of the figure. The equation for the curve shown is:

\[ y \times 10^3 = 13.93 + 3.58 X_L + 7.18 X_Q \]

where \( y = G_2 \) index
\( X_L = 20 \) (radius - .45)
\( X_Q = \frac{3X^2 - 15}{12} \)

Projected polar charts of the G2 index are included in Appendix D. These projected polar charts are graphical representations of the G2 longitudinal growth index. For example, a zero growth index would be depicted by a graph containing an equal number of "projected areas" above and below a line bi-sectoring the quadrant at 45 degrees. It is possible, however, to have a zero growth index and yet have undesirable orientation. Therefore, a "J factor" is calculated that defines whether or not the undesirable orientation is present in the sample. If this value is near one, the orientation is not present (two is generally the worst observed). These values are included in Appendix D. Note that all "J factor" values are quite low on all of the test samples.

5. Bond Strength

Other destructive testing included bond strength determinations. These measurements were taken at various locations on the fuel elements (see Figure 11):

- 5 along the lateral surface
- 2 at the cap-can closure
- 2 on the cap end
- 2 on the base end

Each group of data were analyzed separately.
FIGURE 10

GROWTH INDEX AVERAGE PROFILE
CAP MACHINED TO 0.020 - 0.025 INCHES THICK AFTER CAP CAN PULL

* STUD PULL LOCATIONS FOR BOND STRENGTH DETERMINATION

FIGURE 11
Along the side: A significant difference was found between locations along the side of the fuel element. Average bond strengths over the various test conditions are as follows:

Table III

Average Bond Strength (Side)
(Multiply Values by 33 to Obtain psi)

<table>
<thead>
<tr>
<th>Location</th>
<th>Bond Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 inch from cap</td>
<td>958</td>
</tr>
<tr>
<td>1 inch from cap</td>
<td>1,036</td>
</tr>
<tr>
<td>Center</td>
<td>1,018</td>
</tr>
<tr>
<td>1 inch from base</td>
<td>1,060</td>
</tr>
<tr>
<td>1/2 inch from base</td>
<td>1,141</td>
</tr>
<tr>
<td>Average</td>
<td>1,042</td>
</tr>
</tbody>
</table>

In finding the effects of pressure and time, the average of these five locations were used for each fuel element. No significant effects of pressure and time were noted. This is not surprising in that the different end bonding treatments should not affect the bond strength along the side of the fuel element. The average for the three control fuel elements was 983, which is not different from the average of the various test conditions.

Cap-Can Bond: Again, at the cap-can interface, no effects due to pressure or time were noted. For the various test conditions, the average cap-can bond strength was 966. For the three controls, this was 1050, which is not different significantly from the 966.

Cap and Base End: The cap-end results were appreciably more scattered than the base-end results and standing by themselves should show no significant pressure or time effect. However, they correlate very well with the base end results which, because of the smaller variation, do yield significant effects of both time and pressure. These effects are both linear over the range studied, and no interaction between effects was noted. The mathematical models relating bond strength to pressure and time may be written:

Base End: \[ y = 636 + 154 \phi + 195 \chi_T \]
Cap End: \[ y = 511 + 138 \phi + 118 \chi_T \]

where \( y \) = bond strength
\( \phi \) = (Pressure -5) in tsi
\( \chi_T \) = (Time -40)/10 in. seconds

These models yield the following table of predicted bond strengths. Observed averages are also shown:
Table IV
Average Bond Strength (Ends)
(Multiply Values by 33 to Obtain psi)

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Heat Time</th>
<th>Cap End Predicted</th>
<th>Cap End Observed</th>
<th>Base End Predicted</th>
<th>Base End Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>30</td>
<td>255</td>
<td>321</td>
<td>287</td>
<td>359</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>373</td>
<td>346</td>
<td>482</td>
<td>450</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>491</td>
<td>479</td>
<td>677</td>
<td>600</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>393</td>
<td>391</td>
<td>441</td>
<td>421</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>511</td>
<td>592</td>
<td>636</td>
<td>742</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>629</td>
<td>500</td>
<td>831</td>
<td>817</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>531</td>
<td>517</td>
<td>595</td>
<td>508</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>649</td>
<td>500</td>
<td>790</td>
<td>784</td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>767</td>
<td>954</td>
<td>985</td>
<td>1,042</td>
</tr>
</tbody>
</table>

The controls averaged 1,062 and 1,000 at the cap and base ends, respectively. It is interesting to note that the predictions from the model extrapolated well beyond the range of experimented conditions to the control conditions give predictions for the control of 1,022 on the cap end and 1,555 on the base end. This is not significantly different than observed values of control fuels except the base end, which is unrealistically high.

The bond strength results of this experiment show in summary that increasing either time (temperature) or pressure, or both results in increased bond strengths at the cap and base ends while not affecting bond strengths elsewhere on the fuel elements.

6. Cladding Evaluation

Although no direct correlation has been established between the grain structure and groove corrosion, all test fuels were etched to show grain patterns as a matter of record. Perhaps even more significant than grain patterns is the temperature of cladding during processing. As mentioned earlier, this cladding temperature is considerably below that experienced on fuels currently processed on the standard cycle. The manufacturer has indicated that 8001 aluminum alloy loses part of its corrosion properties if held at an elevated temperature (approximately 550°C) for significant periods of time (minutes to hours). The most rapid deterioration of corrosion properties occurs at approximately 650°C in just a matter of seconds or minutes. Therefore, since these test fuels were processed at a lower temperature, there may be a significant difference in the in-reactor corrosion properties as a result of this temperature drop on the high-pressure test fuels.

Three fuels from each test group were grain etched and macrographs taken of the resultant grain structure on the cladding. It is quite evident from these macrographs that the temperature of the high-pressure test fuels was indeed considerably below that of the control.
fuels (see Figures 12 and 13). Although these samples are only for the controls and the six tsi samples, the same pattern was present on the four and five tsi samples over the time change.

Hardness measurements were taken over the length of these test pieces and followed very closely the grain pattern structure, i.e., large grain areas had low hardness readings. Maximum hardnesses observed were 36 with minimums near the ends of 21 to 27 (see Appendix E).

Grain growth was also observed on a transverse section of the cap and base end of test fuels (see Figures 14 and 15). The control fuel had excessive grain growth on the base I.D. with some evidence on the base O.D. of the fuel. High-pressure fuels, however, show evidence of grain growth only to a very minor degree on the base I.D. of the fuel. The cap end (Figure 15) of the control fuel again had heavy grain growth on the I.D. with a lesser degree of growth on the O.D. cladding. High-pressure fuels, however, had no evidence of grain growth at this magnification.

The samples of Figures 14 and 15 were prepared by etching out the uranium core with boiling HNO₃. Obviously some of the aluminum was also attacked. In Figure 15 the boiling HNO₃ attacked the closure interface. On this small of a sample, it is not possible to make a direct comparison of closure integrity. However, the high-pressure sample showed no evidence of attack at the interface except near the uranium core. Other test fuels showed some evidence of attack, but improved with increasing pressure. More testing is required in this area before it can be stated conclusively that the high-pressure process produces an improved closure. It is, however, equivalent to closures produced on the standard cycle. Further examination of these test pieces indicates that there is no significant difference in nickel dispersion in the cladding at this same area of the base (see Figure 16).

Two test fuels from each test condition were evaluated in the corrosion test defined in Reference 6. Although no correlation between this test and reactor groove corrosion phenomena has been definitely established, the patterns formed by this test very closely approximate the groove corrosion experience in-reactor. Therefore, these fuels were subjected to this test to determine if any gross difference existed between controls and high-pressure test fuels. As can be seen in Figures 17 and 18, there is little difference between control and test fuels. Figure 17 compares a control fuel with a fuel produced at the highest pressure and test temperature. Figure 18 compares a control fuel with a test fuel produced at the lowest pressure and lowest temperature.

The following is a table of weight losses of fuels subjected to this corrosion test:
Figure 12

CAP END GRAIN ETCH
Figure 13

BASE END GRAIN ETCH

UNCLASSIFIED
Figure 14 - ALUMINUM CLADDING GRAIN STRUCTURE (BASE END)
Figure 15

ALUMINUM CLADDING GRAIN STRUCTURE (CAP END)
External

Uranium Side

CONTROL OD CLADDING

External

Uranium Side

TEST CONDITION #9 OD CLADDING

Figure 16

NICKEL DISPERSION
Figure 17

CORROSION TEST COMPARISON
Figure 18

CORROSION TEST COMPARISON
Table V
Average Weight Loss During Corrosion Test (6)

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<th>Average Wt. Loss (Grams)</th>
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<td>50</td>
<td>19</td>
</tr>
<tr>
<td>Controls</td>
<td></td>
<td>24</td>
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</tbody>
</table>

Little difference, if any, was observed with this corrosion test.

7. Uranium Core Evaluation

In addition to the x-ray diffraction growth index tests previously mentioned, the uranium cores were subjected to other destructive testing. Before processing, ten cores were measured for length and for diameter at five positions along the length of the fuel. Following high-pressure end bonding, each fuel was stripped of both cladding and nickel plate. Diameter and length measurements were again recorded. If there was any upsetting of the uranium core during this high-pressure end-bond cycle, it would be reflected in these measurements. Analysis of these measurements indicated no difference in core size (see Appendix F). If the fuel were allowed to attain the temperatures currently produced on standard material at the six tsu pressure, upsetting of the uranium core could conceivably take place. However, because of the reduced threshold bonding temperature required to bond the fuel under this high pressure condition, uranium upsetting is no problem. Maximum warp was 0.002 inches.

To further evaluate the effects of high-pressure end bonding on uranium cores, three cores from each test condition were thermal cycled at 400 C for six hours three times and allowed to air cool between each thermal cycle. By subjecting the fuels to this treatment, any residual stress remaining in the uranium core as a result of the high-pressure end bonding should be relieved and create warp and/or other irregularities in the dimensional stability of the fuel core. Average warp on the as-produced fuels was 0.003 inches, with a maximum of 0.005 inch. After each of the three thermal cycles, the maximum recorded warp was 0.002 inch. Therefore, warp produced as a result of thermal cycling (stress relieving) is non-existant in the high-pressure fuels.
VI. CONCLUSIONS

End bonding HDS fuels at 6 tsi end loading pressure and with a 380 to 420 C end interface temperature (most severe test condition), has no measurable deleterious affect upon the integrity of the bond, cladding, or uranium core. Both destructive and nondestructive ex-reactor testing was employed in this evaluation and revealed no significant difference between the test and control fuels. The end bonds formed at these high-pressure, low-temperature conditions were continuous over the area examined. Bond strengths on test pieces were equal to those on the control fuels. The high-pressure samples had the added effect of reducing the Ni-Al intermetallic formation, thus producing a more ductile diffusion end bond.

No significant difference can be noted in the cladding integrity of these fuels. Although ex-reactor corrosion testing\(^6\) did not indicate a difference between the corrosion properties of test and control fuels, the reduced cladding temperature may improve in-reactor corrosion performance. The cap-to-can closure quality on test fuels is at least equal to that produced on control fuels, with some evidence that it is an improved closure.

Dimensional stability of the uranium core was evaluated by several ex-reactor tests and was found to be no different on test fuels than on control fuels.

VII. RECOMMENDATIONS

All future "8-inch" fuel (diameters less than 1.6 inches) should be produced on the following cycle:

- Pre-Heat Time: 20 ± 5 seconds
- Heat Time: 40 ± 5 seconds
- Hold Time: 55 ± 5 seconds
- Pressure: 6 ± 1/4 tsi

Induction power would be 20 kw for both Pre-Heat and Heat Time. It is further recommended that the Manufacturing Process Specifications, DUN-217, be changed to reflect these operating parameters for high-pressure, low-temperature end bonding.

G. M. Schweikhardt, Engineer
Manufacturing Process Dev. Unit
Manufacturing Engineering Subsection
Production Fuels Section, DUN

GMS:scc
REFERENCES


# APPENDIX A

**CLADDING TEMPERATURE MEASUREMENTS BY POSITION IN THE END BONDER**

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Station No.</th>
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<th>3</th>
<th>4</th>
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<tbody>
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<td>200</td>
<td>220</td>
<td></td>
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<td>320</td>
<td>330</td>
<td>327</td>
<td>315</td>
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</table>

All numbers in degrees centigrade.

Each temperature measurement is average of four readings.

Measured on lateral cladding 1-1/4 inch from cap end of fuel element.
**APPENDIX B**

**Ni-Al Diffusion Thickness Measurements**

<table>
<thead>
<tr>
<th>Test</th>
<th>Condition</th>
<th>No. (Ref. Pg. 8)</th>
<th>Location of Measurement</th>
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<td>1&quot; From Cap</td>
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<td>05 11 12 13 09 14 14</td>
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</table>

All measurements in tenths of mils.

Each value is average of two readings.
APPENDIX C

G-2 LONGITUDINAL GROWTH INDEX

CONTROL
APPENDIX C

G-2 LONGITUDINAL GROWTH INDEX
TEST CONDITION NO. 4

Δ - CENTER
○ - 1" FROM CAP END
□ - 1/2" FROM CAP END

OD - 0.8
.60
.50
.40
.30
ID
RADIUS - INCHES
APPENDIX C

G-2 LONGITUDINAL GROWTH INDEX

TEST CONDITION NO. 5

\[ \Delta - \text{CENTER} \]
\[ \circ - \text{1" FROM CAP END} \]
\[ \square - \text{1/2" FROM CAP END} \]
APPENDIX C

4-2 LONGITUDINAL GROWTH INDEX

TEST CONDITION NO. 6

A - CENTER
O - 1" FROM CAP END
□ - 1/2" FROM CAP END

RADIUS - INCHES

POSITIVE

NEGATIVE
APPENDIX C

5

G-2 LONGITUDINAL GROWTH INDEX

TEST CONDITION NO. 7

---

G-2 GROWTH INDEX (LONGITUDINAL)

NEGATIVE

0.080

0.060

0.040

0.020

0.000

0.000

0.020

0.040

0.060

0.080

RADIUS - INCHES

OD

0.60

0.50

0.40

0.30

0.20

CENTER

1" FROM CAP END

1/2" FROM CAP END

ID - 1878
APPENDIX C

G-2 LONGITUDINAL GROWTH INDEX

TEST CONDITION NO. 8

UNCLASSIFIED DUN-1878
G-2 GROWTH INDEX (LONGITUDINAL)

NEGATIVE

0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00

POSITIVE

0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00

RADIUS - INCHES

DUN. 1978

APPENDIX C

7

G-2 LONGITUDINAL GROWTH INDEX

TEST CONDITION NO. 9

- CENTER

△ 1" FROM CAP END

□ 1/2" FROM CAP END

UNCLASIFIED
APPENDIX D

G-2 PROJECTED POLAR CHART

TEST CONDITION NO. 9
OD READING (SEE APPENDIX C)
1/2" FROM CAP END
J-FACTOR = 1.0184

TOP NUMBER IS THE PLANE DESIGNATION; LOWER NUMBER IS TEXTURE COEFFICIENTS. THIS IS TRUE ON ALL REMAINING PROJECTED POLAR CHARTS.
APPENDIX D

2

G-2 PROJECTED POLAR CHART

TEST CONDITION NO. 9
OD READING
1" FROM CAP END
J-FACTOR 1.0215
APPENDIX D
3
G-2 PROJECTED POLAR CHART

TEST CONDITION NO. 9
OD READING
CENTER OF FUEL
J-FACTOR 1.0179

UNCLASSIFIED
APPENDIX D

5

G-2 PROJECTED POLAR CHART

CONTROL OD READINGS
1" FROM CAP END
J-FACTOR = 1.0318

UNCLASSIFIED
APPENDIX E

Each point represents the average of 12 readings.

- X = Control
- Δ = Low Pressure
- ○ = Medium Pressure
- □ = High Pressure
APPENDIX E

EACH POINT REPRESENTS THE AVERAGE OF 12 READINGS

- X - CONTROL
- △ - LOW TEMPERATURE
- ○ - MEDIUM TEMPERATURE
- □ - HIGH TEMPERATURE

FUEL LENGTH - INCHES
### APPENDIX F

**HDS URANIUM FUEL CORE MEASUREMENTS**

#### BEFORE PROCESSING

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*All measurements in inches.*

*Ref. Page 8*)