CEND-2863-211
Joint U. S. -Euratom
UC-25, Metals, Ceramics
and Materials
TID-4500, 18th Edition

PROGRESS REPORT
THE DEVELOPMENT AND TESTING OF UO₂
FUEL SYSTEMS FOR
WATER REACTOR APPLICATIONS

Period Ending
March 31, 1964

Prepared By:

W. P. Chernock
C. E. Burdg
E. I. Veil
G. Zuromsky

Facsimile Price \$ 4.60
Microfilm Price \$ 1.46

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

Contract AT(30-1)-2863
U. S. Atomic Energy Commission

Issued April 1964

Unclassified
Classification

William H. Simon 4/27/64
Authorized Classifier Date

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

NUCLEAR DIVISION
COMBUSTION ENGINEERING, INC.
WINDSOR, CONNECTICUT

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

CEND-2863-211
Joint U.S. -Euratom
UC-25, Metals, Ceramics
and Materials
TID-4500, 18th Edition

EXTERNAL DISTRIBUTION:

No. of Copies

U. S. Atomic Energy Commission
Technical Information Group
New York Operations Office
376 Hudson Street
New York, New York 10014

30

Mr. J Hart
U. S. Atomic Energy Commission
Contracts Division (Industrial)
New York Operations Office
376 Hudson Street
New York, New York 10014

2

Mr. Harmon S. Potter, Chief
New York Patent Group
Brookhaven National Laboratory
Upton, L.I., New York 11973

1

Dr. J. Frye
Metallurgy Division
Oak Ridge National Laboratory
Post Office Box X
Oak Ridge, Tennessee

1

Dr. Stephen Lawroski
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois

4

Mr. T. Pashos
General Electric Company
Atomic Power Equipment Department
Post Office Box 1131
San Jose, California

1

Dr. R. Allio
Westinghouse Electric Corporation
Atomic Power Department
Post Office Box 1075
Pittsburgh, Pennsylvania

1

CEND-2863-211
Joint U. S. -Euratom
UC-25, Metals, Ceramics
and Materials
TID-4500, 18th Edition

EXTERNAL DISTRIBUTION (Continued):

No. of Copies

Dr. Ersel A. Evans
General Electric Company
Hanford Atomic Products Operation
Richland, Washington

1

Babcock and Wilcox Company
Research and Development Division
Nuclear Development Center
Post Office Box 1260
Lynchburg, Virginia
Attention: Mr. L. R. Weissert

1

THE DEVELOPMENT AND TESTING OF UO_2
FUEL SYSTEMS FOR
WATER REACTOR APPLICATIONS

TABLE OF CONTENTS

	<u>Page No.</u>
List of Figures and Tables	v
Introduction	vii
Abstract	viii
I. Summary	1
II. Thermal Performance Characteristics of UO_2	3
III. Collapse Criteria	12
IV. Projection Welding	15

THE DEVELOPMENT AND TESTING OF UO_2
FUEL SYSTEMS FOR
WATER REACTOR APPLICATIONS

LIST OF FIGURES AND TABLES

<u>Figure No.</u>	<u>Title</u>	<u>Following Page No.</u>
1	3/4" Compound Test Element	11
2	1/2" Test Element	11
3	13 Standpipe Cooling Jacket	11
4	Sight Holes and Post-Test Sections	11
5	Centerline Temperature History	11
6	Effective Conductivity vs. Centerline Temperature	11
7	UO_2 Conductivity vs. Temperature	11
8	Run No. 38 Test Element	11
9	Run No. 38	11
10	Run No. 38 - Section No. 8	11
11	Run No. 38 - Section No. 3	11
12	Collapse Test Specimen	13
13	Tangent Modulus vs. Stress of 347 Welddrawn Stainless Steel Tubing	13
14	Effect of Out-of-Roundness of Tubes in Reducing Maximum Compressive Stress at Collapse Pressure for Various D/T Ratios	13
15	View of Evaluation Subassembly	15

THE DEVELOPMENT AND TESTING OF UO_2
FUEL SYSTEMS FOR
WATER REACTOR APPLICATIONS

LIST OF FIGURES AND TABLES (Continued)

<u>Figure No.</u>	<u>Title</u>	<u>Following Page No.</u>
16	Weld Joint Showing Massive Expulsion of Weld Metal on Indented Side of Spacer Wire	15
17	Appearance of Weld Joint Showing Expelled Metal	19
18	Longitudinal Section of Spacer Wire Showing Weld	19
19	Transverse Section of Spacer Wire Showing Weld	20
<u>Table No.</u>		
1	Collapse Data	13

INTRODUCTION

The United States and the European Atomic Energy Community (EURATOM), on May 29 and June 18, 1958, signed an agreement which provides a basis for cooperation in programs for the advancement of the peaceful applications of atomic energy. This agreement, in part, provides for the establishment of a Joint U.S. -Euratom research and development program which is aimed at reactors to be constructed in Europe under the Joint Program.

The work described in this report represents the Joint U.S. -Euratom effort which is in keeping with the spirit of cooperation in contributing to the common good by the sharing of scientific and technical information and minimizing the duplication of effort by the limited pool of technical talent available in Western Europe and the United States.

THE DEVELOPMENT AND TESTING OF UO_2
FUEL SYSTEMS FOR
WATER REACTOR APPLICATIONS

By

W. P. Chernock, C. E. Burdick, E. I. Veil, and G. Zuromsky

ABSTRACT

Four UO_2 thermal performance elements have been tested, and the results are reported. These results include determination of the effective thermal conductivity of the elements and the high temperature thermal conductivity of UO_2 .

Collapse testing of 3.175 cm diameter tubing with t/R_o values of 0.064 and 0.078 was initiated. Excellent correlation was obtained for tubes with t/R_o of 0.064 for measured collapse pressures and those predicted by either the classical elastic collapse or the tangent modulus criteria. Correlations at the higher t/R_o value, based on only two data points, were not good.

Two-row, 17-tube subassemblies of Type 347 stainless steel have been projection welded to provide tube-to-spacer wire welds of high quality and good dimensional control between centers of tubes (1.587 ± 0.008 cm) lying in a row. Further refinements are being made in cluster support fixtures to eliminate the present problem of lateral misalignment of adjacent rows of tubes prior to the fabrication of the full size 61-tube hexagonal cluster of Type 347 stainless steel.

I. SUMMARY

Four UO_2 thermal performance test elements have been operated.

Centerline temperatures around 2500°C have been routinely reached, and, in each case, the effective thermal conductivity of the element has been determined as a function of centerline temperature. It was found that there is no great change in effective conductivity of the element at center temperatures above 500°C ; the value decreases slowly from about 0.037 to 0.032 $\text{W/cm}^\circ\text{C}$. Thermal conductivity of the UO_2 was determined on three of the four elements. It was found to decrease to a minimum of 0.025 $\text{W/cm}^\circ\text{C}$ at 1500°C , then rise to 0.035 $\text{W/cm}^\circ\text{C}$ at 2200°C . A compound element, consisting of UO_2 surrounded by a ZrO_2 insulating sleeve, has been designed and is being fabricated for future tests.

The pressure vessel body and tubing were received for the collapse test program. Tangent modulus versus stress curves were plotted from stress-strain data obtained for the as-received tubing. Collapse tests were performed and the results, although preliminary in nature, indicate good correlation between measured collapse pressures and those predicted by the elastic collapse or tangent modulus criteria for tubing with a t/R_o ratio of 0.064. For tubing with a t/R_o value of 0.078, collapse pressures 30% greater and 15% lower than those measured were predicted by the elastic collapse and tangent modulus criteria, respectively.

Five 2-row, 17-tube subassemblies of Type 347 stainless steel were fabricated with modified assembly and projection welding techniques to

evaluate tube-to-spacer wire weld quality and control of tube-to-tube dimensions. Improvements in the quality of welds are attributed to the use of a closer dimensional tolerance of ± 0.0013 cm on tube and wire diameters and to refinements in the multiple electrode tooling. Embrittlement of spacer wires at the weld joints has been eliminated by a change in weld schedule. Modifications in tube assembly fixtures has resulted in the control of tube center-to-center spacings to the desired 1.587 ± 0.008 cm dimension for tubes within a row. Excessive lateral displacement between adjacent rows of tubes is being eliminated by further refinements in the cluster assembly fixtures.

II. THERMAL PERFORMANCE CHARACTERISTICS OF UO₂

C. Burdg

A. Introduction

The objectives of thermal performance testing are to determine the thermal conductivity of UO₂, the effective thermal conductivity of a typical fuel element system, and the relationships between microstructure and thermal parameters. The testing is performed by simulation, out-of-pile, of the various thermal conditions which are normally encountered during irradiation of a fuel element. Successful attainment of these objectives will contribute to a better understanding of the mechanisms of heat transfer in UO₂ fuel elements, to more confidence in UO₂ conductivity values, and in the utilization of microstructural analysis as a means of deducing thermal history of an element.

The last quarterly report, CEND-204,* described test work which led to the abandonment of "hot clad" testing. On the other hand, the value of using tungsten alloy heater rods instead of pure tungsten was successfully demonstrated. Direct water cooling of the test element cladding solved the problem of surface heat flux limitation. Experimental work during this quarter has incorporated the changes developed in prior work, with the result that four test elements have been operated with centerline temperatures around 2500°C. The tests have yielded conductivity data up to about 2200°C, and significant microstructural changes occurred as a result of the thermal treatment.

Modification of the shape of the radial temperature profile, in order to produce large amounts of structurally changed UO₂, is one of the

* Chernock, W. P., Burdg, C. E., Veil, E. I., and Zuromsky, G., CEND-204 (January 1964), The Development and Testing of UO₂ Fuel Systems for Water Reactor Applications, Progress Report.

objectives of this program. With the failure of the "hot clad" approach, which was inherently limited by electrical problems, another method was needed. This need has been met by surrounding the UO_2 pellet with an insulating jacket of ZrO_2 . One test element was made this way, and will be tested in the coming quarter.

B. Test Equipment

As described in previous reports, the test element consists of a cylindrical stack of UO_2 pellets, with an axial electrical heater. Temperatures are measured optically at various locations within the UO_2 , as well as on the surface of the heater. Slots cut in the pellets, to selected depths as shown in Figure 4 and Figure 10, provide the optical path to the UO_2 or heater. Tubing "standpipes" are brazed to the clad, and pass through the side wall of the water jacket where they are sealed with O-rings, as shown in Figure 3.

An important change was made in the coolant loop of the test stand. Through run #38, all sample cooling was being done by house-water. An analysis showed that it had about 105 ppm hardness, expressed as CaCO_3 equivalent. When the element was operated at high surface heat flux for an extended period, as in run #38, a severe scaling resulted. To alleviate this situation, the loop was changed to a primary-secondary system, where deionized water forms the primary loop and house-water the secondary loop. The deionized water is recirculated and scrubbed in an ion exchange column, and cooled in a heat exchanger. Thus house-water is still used for heat rejection, but it is not in contact with the test element.

C. Results

1. Run #35

One objective of run #35 was to prove the adequacy of all the prior system modifications: direct water cooling on the clad, use of tungsten-rhenium heater material, and large sighting standpipes. Only seven standpipes were used, and all of these sighted directly on the heater. For this reason only the center temperature could be obtained during the test, giving data only for effective conductivity (that is, the conductivity of the system consisting of UO_2 , gap, and clad) versus centerline temperature. The maximum centerline temperature was 2550°C .* There was no significant change in the effective conductivity with cycling. There was, however, a repeatable knee which occurred at about 500°C centerline temperature; this is probably the result of expansion of the UO_2 into firm contact with the clad and consequent reduction of the pellet-clad thermal resistance.

When the centerline temperature reached about 2350°C , there was rapid grain growth in the bottom of the sight holes, which caused blockage of the sight path within a few minutes. This phenomenon is attributed to vapor phase transport of UO_2 , and deposition in the cooler portions of the system. At this point in the test the center temperature had to be calculated from the electrical resistance of the heater, based on prior calibration and observations at lower temperature.

2. Run #36

Having demonstrated the methods in run #35, #36 was prepared with 13 standpipes so that optical pyrometer readings could be taken

* Figure 5 shows the centerline temperature history for this run.

at a number of radial positions. As before, the conductivity was calculated from the relationship

$$k = \frac{Q \ln R_2/R_1}{2 \pi l \Delta T}$$

where the radii and temperatures are now at selected positions within the UO_2 . Although the test element is 8.5 in. (21.6 cm) long, end conditions have the effect of reducing the length over which the power is dissipated. For purposes of the calculations, the effective length of the element is considered to be 7-3/4 in. (19.7 cm), and the power is considered to be uniform over that length. The values of thermal conductivity thus obtained are for the UO_2 itself, and are plotted against the arithmetic average temperature of the two radii considered for each point.

3. Run #37

An attempt was made to improve the data over that of the previous run, by modifying the depths of some of the sight holes. By providing greater radial separation between the outermost two positions, the temperature difference across that interval would be greater thus giving a more reliable value of conductivity. This did not work well in practice, as the temperature at the outermost position did not reach readable levels early enough in the run to be of much value.

On the first cycle it was observed that the axial temperature profile was not uniform; at an average centerline temperature of $1780^{\circ}C$, the lowest temperature was about $1565^{\circ}C$. This difference, $215^{\circ}C$ or 12%, was roughly twice what had been considered an acceptable variation.

When the situation was confirmed on the second cycle, there was no point in continuing. It was suspected that the UO_2 stack had become loose and the element was removed from the test stand and X-rayed. There was no sign of stack looseness. However, the heater rod was splintered at one end. It was replaced, by driving it out of the stack with a new, sound heater rod. When the element was retested, the axial temperature profile was satisfactory.

On the fourth cycle the center temperature was pushed high enough to permit taking data for UO_2 conductivity determination. During the power reduction portion of the cycle the thermal contraction of the system apparently pulled the heater rod apart, since there occurred a sudden and complete failure of the heater. For this reason there is only one set of data available for UO_2 conductivity, as represented by the single line plot of Figure 7.* Effective conductivity, on the other hand, had been obtained for all the cycles and thus shows as a band of data in Figure 6.*

It might be noted that the value for effective conductivity did not change significantly after changing the heater rod. This is interpreted to mean that peculiarities of the heater-pellet interface are of secondary importance compared to the other parameters in the over-all heat transfer system.

4. Run #38

The first three cycles of run #38 were made to determine the effectiveness of a new set of sight hole dimensions, prior to achieving higher temperature. The data obtained on these cycles helped narrow the spread in UO_2 conductivity values in the region of 1000 to 1600°C. The next cycle was then aimed at operation for 24 hours with a centerline temperature

* The boundaries of the curves in Figures 6 and 7 represent scatter from all data points obtained during a given run.

of about 2500°C.

Target test conditions were achieved with a minimum of trouble, and the extended run started. At about 13 hours at 2500°C, there was a momentary excursion upward in temperature, as evidenced by a "bump" in the meters monitoring the heater power, voltage and current. Minor corrections were made, and the element behaved in a normal, stable manner. However, the appearance of the bottom of sight hole #3 shifted from usable to a very granular texture, indicating that a temperature excursion could have occurred at that location. At about 20 hours, a dynamic disturbance was observed at the bottom of sight hole #3. The disturbance was similar to "sparklers" or minute flashes of brilliant light, shooting upward in the standpipe, for a distance of perhaps 3 cm. Even though there was no indication of instability on the electrical metering, the visual effect was not one to instill confidence in continued successful operation. The power was discontinued.

Even though test run #38 ended in element failure, there were enough data obtained to determine conductivity values, which appear in Figure 7. As before, there was no change in k_{eff} with temperature or with time at power.

The probable cause of failure was revealed on post-test examination of the element. Figures 8 and 9 show the heavy mineral scale which had built up on the element in two regions: first, at the two ends adjacent to the O-ring seals, where there is a short section of clad not in contact with the coolant. Second, in a band in the vicinity of sight hole #3. Both these areas were continuously exposed to flowing water, so the scale

would build up only if there were a localized high clad temperature. From the appearance of the scale, it was suspected to be CaCO_3 . This was confirmed by X-ray diffraction analysis.

Run #38 was the first test where surface heat flux as high as 65 W/cm^2 had been maintained for more than a few hours. The scaling process was apparently proceeding during the test; then, when the thermal excursion occurred at 13 hours, the scaling around standpipe #3 was accelerated. By 20 hours, the heat transfer to the cooling water became so poor that the center-line temperature rose enough to melt the UO_2 . This, in turn, changed the geometry enough to cause the heater to melt. However, the molten UO_2 had enough electrical conductivity to allow the current to continue flowing, so there was no evidence on the external metering. It was probably at this time that the "sparklers" were seen in standpipe #3.

A longitudinal section of the element is shown in Figure 11. The arrows indicate the original pellet/pellet interfaces, which are now bridged over in the higher temperature regions.

5. Run #39

Work was started on the preparation of the sample for run #39. This is a compound element, as shown in Figure 1. The reason for the configuration is to obtain a radial temperature profile which results in more of the UO_2 being at very high temperature than is the case with the simple configuration of Figure 2. The dimensions are approximately as follows:

	<u>Inches</u>	<u>Centimeters</u>
Heater diameter	0.075	0.190
UO ₂ diameter	0.337	0.856
ZrO ₂ diameter	0.714	1.814
Clad diameter	0.750	1.905
Clad wall thickness	0.017	0.043

Because the ZrO₂ has a thermal conductivity which is much lower than UO₂, particularly at lower temperatures, it is expected that most of the UO₂ will reach temperatures above 1400°C. The value of reaching such a condition is twofold: first, more data for determining thermal conductivity of UO₂ at high temperature will have been obtained; and second, the influence of temperature and temperature gradient on microstructural change will be determined at profile conditions quite different from the previous tests in this program.

D. Conclusions

The results of tests 36, 37 and 38, shown in Figure 7, lead to the conclusion that the thermal conductivity of sintered UO₂ pellets decreases to a value of about 0.025 W/cm°C at about 1500°C, then rises to about 0.035 W/cm°C at 2200°C. The results are combined, and compared to the low temperature results reported by Daniel, et al,* for unirradiated, polycrystalline UO₂. The match with Daniel's curve, at around 1000°C, shows reasonable agreement considering the vastly different methods used to determine thermal conductivity.

* Daniel, J. L., Matolich, J., and Deem, H. W., HW-69945, September 1962, Thermal Conductivity of UO₂.

This work indicates thermal conductivity to be perhaps 20% higher than Daniel's curve, at 1000°C. Daniel has corrected all his data to 100% of theoretical density.

A second conclusion is that the effective conductivity of these test specimens did not change with centerline temperature above 500°C. Figure 6 shows the effective conductivity for four runs; as centerline temperature is increased, the k_{eff} increases rapidly, until the UO_2 has apparently expanded to close the pellet clad gap at about 500°C. Above that temperature, the k_{eff} is almost constant. The values were closely repeatable from cycle to cycle, and did not change even when the heater rod was changed as in run #37. From this it is concluded that the effects of cracks in the pellets are not large compared to the bulk effects in the UO_2 . If such were not the case, there would be noticeable differences on successive cycles.

Microstructural changes appeared within the UO_2 in the region of high temperature and high temperature gradient near the heater. No conclusions are drawn as the data are not yet analyzed.

E. Future Work

Runs #39 and #40, consisting of compound elements, will be made and the data analyzed. The thermal conductivity data so obtained will be combined with those from all the other data on this program, and a composite result determined. Analysis of microstructures will be completed.

3/4" COMPOUND TEST ELEMENT

Fig. 1

1/2" TEST ELEMENT

Fig. 2

2441

13 STANDPIPE COOLING JACKET

* - THIS SURFACE PREPARED FOR METALLOGRAPHY

SIGHT HOLES AND POST-TEST SECTIONS

EFFECTIVE CONDUCTIVITY vs. CENTERLINE TEMPERATURE

Fig. 6

UO₂ CONDUCTIVITY vs. TEMPERATURE
Fig. 7

2364

RUN No. 38 TEST ELEMENT

Fig. 8

2365

4.5X

RUN No. 38

Fig. 9

2444

8.6X

RUN No. 38 SECTION No. 8

Fig. 10

2442

4.5X

RUN No. 38 SECTION No. 3

Fig. 11

A. Introduction

Previous work at CEND has established the validity of the "Tangent Modulus Criterion" for predicting collapse pressures of stainless steel tubing with diameters up to 1.9 cm (0.750 in.) and tube thickness to radius ratios (t/R) up to 0.012. The present program was initiated to determine whether this criterion can be applied to tubing with diameters in the range of 2.5 to 3.8 cm (1.0 to 1.5 in.).

In a previous quarterly progress report, CEND-199,* a number of factors were discussed which influence collapse. One of these factors was the ratio of unsupported tube length to diameter (L/D) required to represent infinite tube lengths. It has been established** that an infinite tube length is adequately represented at t/R_0 values greater than 9 for 1.9 cm diameter tubes with wall thickness in the range of 0.05 to 0.124 cm.

On the basis of these data a pressure vessel body was purchased which, conservatively, will accommodate "infinite length" samples with an outside diameter of 3.8 cm.

B. Experimental Effort

The pressure vessel body has been received and installed. Type 347 weldrawn annealed tubing, 3.175 cm (1.250 in.) in outside diameter, with six different wall thicknesses in the range of 0.07 and 0.19 cm (0.028 and 0.075 in.) has been received. Stress-strain data were obtained from tensile

* Chernock, W. P., Burd, C. E., Andrews, M. G., Veil, E. I., and Mordarski, W. J., CEND-199 (November 1963), The Development and Testing of UO_2 Fuel Systems for Water Reactor Applications, Progress Report.

** Chernock, W. P., Burd, C. E., Veil, E. I., and Zuromsky, G., CEND-204 (January 1964), The Development and Testing of UO_2 Fuel Systems for Water Reactor Applications, Progress Report.

tests of two samples from each wall thickness size. All of the 0.2% offset yield strength values were in the range of 2450 to 2730 kg/cm² (35,000 to 39,000 psi) with the exception of samples with 0.07 and 0.10 cm wall thicknesses. Values from these thinner tubes were in the range of 3290 to 3430 kg/cm² (47,000 to 49,000 psi). This increase was a result of the final sizing pass used at the mill.

Specimens 3.175 cm in outside diameter with a 0.10 and 0.12 cm wall thickness (Figure 12) have been fabricated and collapsed at room temperature. Test data are shown in Table 1. Figure 13 is a plot of the average Tangent Modulus (E_T) versus stress for the 0.10 and 0.12 cm wall thickness tubing. Data shown in Figure 14 were used in correcting for ovality.

On the basis of data from a limited number of samples, definitive conclusions cannot be made. However, an analysis of these initial data indicates that, at a t/R_o of 0.064, the classical elastic collapse criterion provides a more accurate prediction of collapse pressure than the "Tangent Modulus Criterion." Similar results were found in earlier work* for smaller diameter tubing. The earlier effort indicated the need for the tangent modulus approach only when t/R_o ratios exceeded 0.07.

Trends established in CEND-157* appear to be in evidence in the current series of tests with larger diameter tubing. At a t/R_o value of 0.078, the classical collapse equation predicts a collapse pressure 30%

* Murtha, B. E., and Chernock, W. P., CEND-157 (June 1962), The Development and Testing of UO₂ Fuel Systems for Water Reactor Applications, Summary Report.

COLLAPSE TEST SPECIMEN

TANGENT MODULUS vs. STRESS OF 347
WELDDRAWN STAINLESS STEEL TUBING

DATA TAKEN FROM T. JASPER "COLLAPSING STRENGTH OF STEEL TUBES" ASME TRANSACTIONS Vol. 53 1931, APM 53-17b 219

EFFECT OF OUT-OF-ROUNDNESS OF TUBES IN REDUCING MAXIMUM COMPRESSIVE STRESS AT COLLAPSE PRESSURE FOR VARIOUS D/T RATIOS

Fig. 14

TABLE 1. COLLAPSE DATA

Sample Number	Material	Avg. Wall Thickness (cm)	Avg. OD (cm)	$\frac{t}{R_o}$ ^(a)	Ovality ^(b)	Avg. 0.2% Offset Y. S. (kg/cm ²)	Actual Collapse Pressure (kg/cm ²)	Actual ^(c) Collapse Pressure Corrected for Ovality (kg/cm ²)	Predicted ^(d) Collapse By Tangent Modulus (kg/cm ²)	Predicted ^(e) Collapse By Elastic Criterion (kg/cm ²)
CT-A-40-1	347	0.10	3.172	0.064	0.04	3358	131.3	135.1	139.7	135.5
CT-A-40-2	347	0.10	3.172	0.064	0.04	3358	127.8	131.6	139.7	135.5
CT-A-49-1	347	0.12	3.177	0.078	0.20	2511	157.5	167.7	135.1	225.3
CT-A-49-2	347	0.12	3.176	0.078	0.28	2511	155.8	167.3	135.1	225.3

(a) t/R_o = Average Wall Thickness $\div$ Radius

(b) $\frac{D_{\max} - D_{\min}}{D_{\min}} \times 100\%$ where D = Outside diameter

(c) Reference: "Collapsing Strength of Steel Tubes," ASME Transactions, Vol. 53, 1931, APM-53-17b-219.

(d) $P_c = \frac{E_t}{4(1 - a^2)} (t/R_o)^3$ E_t = Tangent Modulus
 a = Poisson's Ratio

Reference: "The Development and Testing of UO₂ Fuel Systems for Water Reactor Applications," CEND-157, June 1962.

(e) $P_c = \frac{E}{4(1 - a^2)} (t/R_o)^3$ where $a = 0.284$, and
 E = Young's Modulus

greater than that observed. The tangent modulus method predicted a collapse pressure which is 15% lower than that observed. The accuracy of both methods is not good; however, the tangent modulus approach has provided a value which is conservative. Although corrections for ovality have been made, a question is raised as to whether an ovality of 0.3% or less reduces the actual collapse pressure. Collapse occurred in sample CT-A-49-2 as expected in an area of maximum ovality; whereas sample CT-A-49-1 which exhibited a uniform ovality along its entire length collapsed at almost the identical pressure. Tubing of the same lot as samples CT-A-49-1 and -2 will be examined in search for lengths with ovality below 0.1%. Testing of this tubing will provide data concerning the influence of ovality. The possible influence of eccentricity will also be assessed.

Test data from the entire series of t/R_o values from this program must be obtained and analyzed before definitive conclusions can be made concerning the applicability of the "Tangent Modulus Criterion" for predicting collapse of large diameter tubes.

C. Future Work

The program on 3.175 cm diameter tubing will be completed. Deviations from values predicted will be assessed with the object of introducing modifications to the equation to provide collapse criteria for the range of tube diameters under investigation. A few tests at 550°F may be included as final demonstration of the validity of the selected collapse criterion.

IV. PROJECTION WELDING

G. Zuromsky

A. Introduction

The objectives of the effort during the present reporting period were to refine electrode tooling, cluster fixturing and welding parameters. The first phase of this development effort is concentrated on improved fabrication development and evaluation of a number of 2-row, 17-tube subassemblies (Figure 15) of Type 347 stainless steel. This effort is to be followed by the fabrication of a 61-tube assembly for differential thermal elongation tests. The second phase of this program will concentrate on the development of inert gas, projection welding techniques for Zircaloy-2 subassemblies, culminating in the fabrication and testing of a 61-tube assembly.

Progress during this reporting period centers on the fabrication and evaluation of stainless steel subassemblies.

B. Experimental Effort

Variability in weld quality and tube-to-tube dimensions as well as spacer wire embrittlement has been attributed to improper control of tube and wire cleanliness and dimensions as well as improper jiggling during welding.

Process improvements are summarized below:

1. Type 347 stainless steel tubes, 1.27 cm OD by 0.051 cm wall, and spacer wire, 0.158 cm in diameter, were purchased in the bright annealed condition with a dimensional tolerance of ± 0.0013 cm (0.0005 in.) on the tube OD and on the wire diameter. Closer control of dimensions will significantly reduce variations in the effective electrode force on the spacer wires. As an example, if the tube OD is undersize, some of the electrode force is used in

MAG 1/4X

VIEW OF EVALUATION SUBASSEMBLY

Fig. 15

MAG 10X

*WELD JOINT SHOWING MASSIVE EXPULSION OF WELD
METAL ON INDENTED SIDE OF SPACER WIRE*

Fig. 16

bending the wire into contact with the tube, resulting in a decrease in wire setdown and a reduction in spacing between adjacent tubes. The use of bright annealed tubes and spacer wires will prevent the formation of inclusions and gas voids in the weld nuggets due to surface contamination (oxides, drawing compounds, mill dirt).

2. As a target for this program, it was desired to maintain the 1.587 cm (0.625 in.) distance between tube centers to ± 0.008 cm (0.003 in.) while maintaining an over-all cluster envelope of ± 0.102 cm (0.040 in.). In order to meet these requirements, the cluster support fixture was reworked to permit control of tube-to-tube spacing to the desired ± 0.008 cm. Additional tie bars were included in the support fixture to provide a more rigid restraint of assembled tubes during welding. Accurately positioned spacer rods were inserted into both ends of the row of tubes to maintain the tube-to-tube distance.

3. Copper mandrels about 6.35 cm (2.5 in.) in length were inserted into the tubes to prevent indentation of the tube wall during welding. Indentation was limited to 0.003 cm (0.001 in.) maximum in order to allow subsequent loading of the tubes with closely dimensioned fuel pellets. Tube wall indentation was reduced to less than 0.003 cm as a result of mandrel adjustments.

The previous differential thermal expansion test on a stainless steel cluster revealed that some failures had occurred after 2,000 cycles through an embrittled region of the spacer wire at the weld joint. Subassemblies were fabricated under identical conditions to determine whether embrittlement could be attributed to the wire composition or to the welding

procedure. Wires of Type 347 stainless steel welding composition, * used previously, and of nominal composition* were used in these evaluations. A controlled wave welder using a four cycle weld schedule was employed to reduce the time at welding temperature and thereby reduce the heat effect on the wire.

Four stainless steel subassemblies were fabricated at Sciaky to evaluate the relative ductility of the two wire compositions, weld quality and dimensional control. An additional subassembly was fabricated subsequently with emphasis on dimensional control of tube center to tube center distance. Further modifications were made on the electrode tooling and assembly fixtures with the intent of improving weld quality. Three subassemblies were measured to obtain tube center to tube center distances and selected welds from all subassemblies were examined metallographically for nugget size, symmetry and penetration into the tube wall.

C. Results and Discussion

Visual examination at a magnification of 10X of the four stainless steel subassemblies revealed severe electrode indentation of the spacer wires for approximately 10% of the weld joints. The indentations were due to slight misalignment of the upper electrodes which exerted an eccentric force on the wires. These weld joints exhibited excessive weld metal expulsion on the

*	<u>Composition of Type 347 Stainless Steel Spacer Wires</u>	
	<u>Nominal</u>	<u>Welding Type</u>
C	0.07%	0.07%
Mn	0.57	1.50
Si	0.42	0.30
Cr	19.14	20.00
Ni	8.58	10.00
Cb + Ta	0.83	0.80

indented side of the spacer wire (Figure 16). Metallographic evaluation revealed non-symmetrical welds with gross localized melting of the indented portion of the wire. Other weld joints which did not show spacer wire indentation contained symmetrical weld nuggets which were centrally located on the tube-wire interface. Weld penetration into the tube wall varied from about 25 to 50% of the wall thickness. All welds examined were essentially free of injurious defects including voids, inclusions and fissures. There was no evidence of cracks in the tube wall or in the spacer wires adjacent to the welds. The spacer wires of the two compositions showed no loss in ductility after bending the weld heat-affected portions to an angle of 90°. This improved ductility is attributed to the use of a steeply peaked weld cycle in lieu of the previously uniform 5-cycle weld schedule. The coarse dendritic structure along with the shrinkage cavity or pipe within the expelled metal has been significantly reduced by the present welding technique.

Dimensional inspections at both ends of two assemblies showed tube center-to-center spacings of $1.587 \begin{smallmatrix} +0.030 \\ -0.025 \end{smallmatrix}$ cm ($0.625 \begin{smallmatrix} +0.012 \\ -0.010 \end{smallmatrix}$ in.) for tubes within a row. Due to skewing of the two rows, the diagonal spacing between centers of adjacent tubes varied from 1.575 to 1.618 cm (0.620 to 0.637 in.). Similar lateral misalignment or skewing of the tube rows was observed for all four subassemblies.

The fifth subassembly was fabricated following further modifications in tooling and fixturing to improve electrode-spacer wire alignment and to control tube center-to-center spacing to 1.587 ± 0.008 cm (0.625 ± 0.003 in.). Visual inspection showed that electrode indentation of the spacer wires had been

essentially eliminated with a corresponding balance of expelled weld metal on both sides of the joint. Shrinkage voids or pipes, noted previously, were absent in the reduced volumes of expelled metal (Figure 17). Dimensional measurements of center-to-center spacings for tubes lying in rows and between rows are shown below.

Tubes Within Row

First End	8-tube row	$1.587 \begin{smallmatrix} +0.008 \\ -0.008 \end{smallmatrix}$ cm	$(0.625 \begin{smallmatrix} +0.003 \\ -0.003 \end{smallmatrix}$ in.)
	9-tube row	$1.587 \begin{smallmatrix} +0.003 \\ -0.008 \end{smallmatrix}$ cm	$(0.625 \begin{smallmatrix} +0.001 \\ -0.003 \end{smallmatrix}$ in.)
Opposite End	8-tube row	$1.587 \begin{smallmatrix} +0.003 \\ -0.008 \end{smallmatrix}$ cm	$(0.625 \begin{smallmatrix} +0.001 \\ -0.003 \end{smallmatrix}$ in.)
	9-tube row	$1.587 \begin{smallmatrix} +0.008 \\ -0.008 \end{smallmatrix}$ cm	$(0.625 \begin{smallmatrix} +0.001 \\ -0.001 \end{smallmatrix}$ in.)

Tubes Between Rows

First End	$1.587 \begin{smallmatrix} +0.020 \\ -0.005 \end{smallmatrix}$ cm	$(0.625 \begin{smallmatrix} +0.008 \\ -0.002 \end{smallmatrix}$ in.)
Opposite End	$1.587 \begin{smallmatrix} +0.033 \\ -0.003 \end{smallmatrix}$ cm	$(0.625 \begin{smallmatrix} +0.013 \\ -0.001 \end{smallmatrix}$ in.)

The data show that the dimensional requirement of 1.587 ± 0.008 cm (0.625 ± 0.003 in.) has been maintained for the center-to-center spacing of tubes lying within rows. However, lateral displacement between tube rows had caused the triangular pitch of tubes (center spacings) between rows to vary from -0.003 to -0.005 cm (-0.001 to -0.002 in.) to $+0.020$ to $+0.033$ cm ($+0.008$ to $+0.013$ in.) of the nominal value of 1.587 cm. Additional refinements will be made in the cluster support fixtures to maintain the tube center triangular pitch dimension to 1.587 ± 0.008 cm. Control of this dimensional tolerance will influence the ability to attain the desired envelope tolerance on the 9-row, 61-tube clusters.

2440

MAG 24X

APPEARANCE OF WELD JOINT SHOWING EXPELLED
METAL

Fig. 17

2448

MAG 40X

LONGITUDINAL SECTION OF SPACER WIRE
SHOWING WELD

Fig. 18

Metallographic examination of longitudinal and transverse sections of randomly selected weld joints showed welds of suitable quality in relation to soundness, symmetry and penetration into the tube wall and spacer wires. Improvement in the surface cleanliness of tubes and spacer wire has resulted in welds which are essentially free from gas voids and inclusions. Shrinkage cracks of the type shown in Figure 18, although undesirable, may have no significant effect* on the strength properties of the weld joint on the basis of their orientation and location within the welds. Welds of this type have survived 2,000 thermal cycles.** Figure 19 illustrates the uniformity of weld metal expulsion and the depth of the fused nugget into the tube wall.

D. Thermal Tests

Differential thermal elongation tests will be conducted on full-scale projection-welded clusters fabricated from Type 347 stainless steel and Zircaloy-2, respectively. These tests will investigate the capability of the clusters to structurally withstand cyclic changes in tube-to-tube temperatures of 10°C (20°F) for a total of 3,000 temperature reversals.

Redesign of the test apparatus is nearing completion, and assembly will be completed in May. A new concept for the manifold-cluster assembly has been evolved. One problem on the previous test was associated with misalignment between individual tubes and the counterbored holes which caused a binding problem and changed the stress pattern of the system. The modified

* Welding Handbook, American Welding Society, 4th Ed., Sec. 2 (1958), p. 30.49.

** Chernock, W. P., Burdg, C. E., Andrews, M. G., Veil, E. I., and Mordarski, W. J., CEND-199, (November 1963), The Development and Testing of UO₂ Fuel Systems for Water Reactor Applications, Progress Report.

2447

MAG 40X

*TRANSVERSE SECTION OF SPACER WIRE
SHOWING WELD*

design employs an individual fitting for each tube. A flexible rubber tube will connect each fitting to its respective manifold away from the end of the cluster. A shoulder on the outside of each fitting will rest on a washer and provide the vertical support without restraint of the tubes. The tubes will be permitted to move vertically relative to each other as influenced by differences in temperature.

E. Future Work

A final stainless steel subassembly will be fabricated and evaluated to demonstrate that inter-row tube-to-tube dimensions can be maintained within the ± 0.008 cm (± 0.003 in.) tolerance. The assembly and projection welding techniques developed during the program will be utilized in the fabrication of a 213.4 cm (7-foot) long, 61-tube hexagonal cluster of Type 347 stainless steel. Differential thermal elongation tests on this cluster will be initiated. Welding methods and fixturing developed for stainless steel tubing will be modified to provide an inert gas atmosphere for welding development for Zircaloy-2 tubes. Subassembly welding development and testing will be followed by the fabrication of a 61-tube cluster for differential thermal elongation testing.

LEGAL NOTICE

This document was prepared under the sponsorship of the Euratom Commission pursuant to the Joint Research and Development Program established by the Agreement for Cooperation signed November 8, 1958 between the Government of the United States of America and the European Atomic Energy Community (Euratom). Neither the United States, the U.S. Atomic Energy Commission, the European Atomic Energy Community, the Euratom Commission, nor any person acting on behalf of either Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this document, or that the use of any information, apparatus, method, or process disclosed in this document may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method or process disclosed in this document.

As used in the above, "person acting on behalf of either Commission" includes any employee or contractor of either Commission or employee of such contractor to the extent that such employee or contractor or employee of such contractor prepares, handles, disseminates, or provides access to, any information pursuant to this employment or contract with either Commission or his employment with such contractor.