UNCLASSIFIED

ANL-5110(Del.)

ARGONNE NATIONAL LABORATORY
P. O. Box 299
Lemont, Illinois

Photostat Price \$ 7.80

Microfilm Price \$ 3.30

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

DEVELOPMENT OF A PROCESS TO PRODUCE ZIRCONIUM HANFORD
TYPE PROCESS TUBING BY ROLL FORMING AND INERT ARC WELDING

by

R. A. Noland and G. B. O'Keeffe

DELETED VERSION

Classification change to Unclassified
Authorized by R. L. Morgan 2-12-57
Change by H. Kinder Date 6-13-12

May 1, 1953

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, express 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 to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

Operated by The University of Chicago
under
Contract W-31-109-eng-38

UNCLASSIFIED

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.

TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	4
II. ABSTRACT.	7
III. DISCUSSION	8
A. Preparation of Ribbed Strip	8
B. Roll Forming, Welding, and Cold Finishing	12
C. Testing of the Tubing.	15
IV. CONCLUSIONS	17
REFERENCE	18
FIGURES AND TABLES	19

DEVELOPMENT OF A PROCESS TO PRODUCE ZIRCONIUM HANFORD TYPE PROCESS TUBING BY ROLL FORMING AND INERT ARC WELDING

I. INTRODUCTION

Hanford process tubes (Figure 1) are inserted in the graphite moderators of the Hanford reactors and carry the fuel slugs and the cooling water. The slugs are borne by two long rails, 90 degrees apart, which run parallel to the longitudinal axis of the tubes, the rails serving to hold the fuel away from the tube wall to allow water access to the slugs.

These tubes have been made of aluminum by extrusion ever since Hanford started up, and have performed well in service under the reactor conditions which have been imposed on them.

For the past few years a great amount of attention has been focused on a new reactor material, zirconium, which is known to have excellent nuclear properties in all types of reactors. It is stronger than 2S aluminum (Table I), has superior corrosion resistance under many conditions, and it can be fabricated fairly economically depending on conditions of use, although with less facility than aluminum. Cost of the raw metal, however, is considerably greater than that of aluminum, being at least 100 times more expensive in billet form.

In addition to considering zirconium for new reactors, reactor engineers have studied the possibility of its use in existing reactors, among them the Hanford reactors. Zirconium could possibly achieve neutron economy at Hanford if it were used to make process tubes. A reduction of the wall from the present average of 0.065 in. required for aluminum to 0.030 or 0.040 in. would reduce the amount of zirconium used, and therefore the cost of these tubes would be lower.

A superficial glance at the question of zirconium versus aluminum in Hanford indicates that zirconium is the outstanding choice if these reactors are operated at a higher temperature with the present type of water on a once through basis, but this may not be true if closed system high purity water were used. Additional data obtained by actual manufacture of a test group of tubes, and reactor and other tests on these tubes would possibly be helpful to existing evaluations.

The Metallurgy Division was originally asked to develop a method to make a zirconium Hanford type process tube by an evaluating group at Argonne under a program known as the Hannah Project, and a request was

DECLASSIFIED

also received from the Washington Office of the AEC. A number of methods were considered, and all but one were rejected for the following reasons:

1. Not feasible.
2. Feasible but expensive.
3. Expensive and equipment not available.

The various methods considered were:

A. Extrusion

1. Extrude shape with rails oversize, and cold reduce by swaging, tube reducing, or cold drawing. Method considered to be quite feasible, although possibly more expensive than another method. Extrusion facilities not readily available.

2. Extrude to size with rails integral. On basis of known information it was not believed that desired tolerances would be obtained by this method.

3. Extrude round tube oversize and cold work rails out of material in wall by swaging, drawing, or tube reducing. 3. considered to be more expensive than 1. above, and probably less likely to succeed. No apparent advantage over 1.

B. Roll Forming and Inert Arc Welding

1. Roll form and weld heavy walled tube and cold work to finished shape on tube reducer, swager, or draw bench. Method considered feasible if cold working were to be done in several operations, annealing in process if necessary. Strip was prepared, and arrangements were made with commercial concerns for use of their personnel and tools for roll forming and welding (Trent Tube Company) and tube reducing (Tube Reduction Corporation). This approach was dropped after the strip was made, when it was learned that another AEC facility was attempting to use the same method.

2. Roll form and weld tube leaving wall thickness slightly greater than desired final wall, and series resistance weld cold formed rails in place inside tube, later finishing to final size on swager, draw bench, or tube reducer. Other methods appeared to be simpler, especially because of the need for expensive special tooling such as a custom made seam welder equipped with ninety degree welding head for series seam welding.

3. Roll form and weld slightly oversize tube from flat strip with integral or welded rails, and cold finish to final size by swaging, drawing, or tube reduction. Of all the methods considered, the above was believed

DECLASSIFIED

to offer the greatest promise from the standpoints of cost and quality. High grade zirconium strip easily inspectable on both sides can readily be made to high standards of quality, and it is possible that it might even be made with the rails integral if appropriately shaped rolls were developed. If integral rails were not desired, individual rails were believed to be easily fabricable by cold rolling from a round. It is known that zirconium can be resistance welded with facility, and the rails could be so fastened to the sheet. Argonne had previously made some very satisfactory round tubing of approximately the desired size by roll forming and inert arc welding Grade III crystal bar strip at the Trent Tube Company plant in East Troy, Wisconsin (ANL-5138),⁽¹⁾ experience which indicated the feasibility of processing zirconium into tubing in this manner, although it was reasonable to question whether the proposed ribbed strip would perform in the same fashion as a flat. Some reason for question also was justified regarding the possibility that the as-welded tube, most likely with flats on the outer diameter adjacent to the rails, could be economically finished within reasonable tolerances by the suggested cold reducing techniques.

Tubing of the highest quality can be produced by inert arc welding. This is especially true of stainless steel tubing which when inert arc welded generally is priced at a lower level than seamless tubing made by hot piercing and cold drawing. It was believed that the same low costs would be incurred in making zirconium welded process tubing, allowing some extra charges for forming and welding the rails to the tube strip.

Inert arc welds of excellent quality are not difficult to produce in zirconium, especially under the conditions present during continuous roll forming when the butted tube seam is passed continuously under a helium shielded W-electrode which is supplied current under stable electrical and mechanical conditions. Because the weld is the area under the greatest suspicion in a welded tube, it is important to know that good welds are easily made.

In view of the considerations outlined above, we decided to concentrate on attempts to manufacture a zirconium process tube of approximate Hanford dimensions by utilizing procedure B-3. Ribs were to be cold rolled and resistance welded instead of being rolled integral with the tube strip to eliminate the development necessary on roll design and to save the time and cost of such development, including the cost of rather expensive tools. Whether the rib was or was not integral did not seriously compromise the merit of the suggested method because the most important steps requiring actual demonstration were the roll forming of the ribbed flat, and the finishing of the welded tube within acceptable tolerances. Unfortunately, Bureau of Mines consumable electrode arc melted zirconium was not available for this work, and we were forced to use Grade III arc melted crystal bar zirconium, an excellent but rather expensive grade of material.

DECLASSIFIED

The crystal bar was arc melted and worked into 0.065 in. sheet at Argonne by members of the Foundry and Fabrication group led by Mr. R. E. Macherey. Tools for forming the rib were designed at this laboratory, and used at the Corey Steel Company of Cicero, Illinois, whose Mr. W. D. Perkins permitted the use of their facilities. Resistance welding of the rails to the sheet was done at Sciaky Brothers, Incorporated, of Clearing, Illinois, with laboratory designed wheels and fixtures. The Trent Tube Company of East Troy, Wisconsin, a division of the Crucible Steel Company, formed, welded, and finished the tubing.

We gratefully acknowledge the suggestions and assistance of the organizations mentioned and their personnel, as well as of those people at the Argonne National Laboratory who were responsible for the fabrication of the necessary material. In particular, we would like to mention our gratitude to the following:

Corey Steel Company - Mr. W. D. Perkins
Sciaky Bros., Inc. - Messrs. Paul Yankala and W. J. Farrell
Trent Tube Company - Messrs. H. J. Bowman, E. Williams
and Joseph Olson
ANL - Messrs. R. E. Macherey, R. J. Dunworth, H. J. Luetzow
and W. E. Ruther

II. ABSTRACT

The development of methods which were successful in producing zirconium Hanford type process tubing by roll forming and inert arc welding (He) flat strip to which appropriate rails had been previously attached by resistance welding is described in this report. Grade III drip arc melted crystal bar material was used.

Tubing, leak free and acceptable to corrosion tests in 200°C water, and to other physical tests, was made on the first try on a Yoder type tube mill.

Dimensional correction of the as-welded tube was accomplished by cold swaging on a shaped mandrel. Straightening and removal of twist from the tubing was readily accomplished.

Production rates and costs for roll forming and welding are estimated to be quite similar to costs for the same operations performed on the austenitic stainless steel grades. Tube welding speeds were approximately 20 in. per minute. Welding of the rails to the sheet was done at around 24 in. per minute.

Shortage of material limited the length of tubing made, but the work done clearly indicated that lengths of 50 to 60 ft. could be made easily, and that the ultimate length possible to manufacture is limited principally by the length of the tube strip.

A 3x10 grid of dots forming the word "REASON". The dots are arranged in three rows and ten columns. The first row contains dots at (1,1), (1,2), (1,3), (1,4), (1,6), (1,7), (1,8), (1,9), (1,10), and (1,11). The second row contains dots at (2,1), (2,2), (2,3), (2,4), (2,6), (2,7), (2,8), (2,9), (2,10), and (2,11). The third row contains dots at (3,1), (3,2), (3,3), (3,4), (3,6), (3,7), (3,8), (3,9), (3,10), and (3,11). The word "REASON" is formed by the pattern of dots.

III. DISCUSSION

Essentially the process developed may be described and divided into three sections, the first dealing with the preparation of the ribbed strip; the second describing the roll forming and welding of the ribbed strip into a tube, and the cold finishing of the welded tube to the desired final size; and the third listing the testing of the finished tubing.

A. Preparation of Ribbed Strip:

1. Fabrication of Flat Zirconium Strip.

A rolling billet, 6 in. in diameter by 13-3/4 in. long, weighing 40.6 kg was drip arc melted by R. J. Dunworth, employing a water-cooled W-tipped copper electrode.⁽¹⁾ Melting was done against a zirconium dummy in an arc melting furnace which was provided with a water-cooled copper crucible and an inert atmosphere composed of 20 per cent argon and 80 per cent helium.

The billet was forged in air at 800°C by the Anderson-Schumaker Company of Chicago, Illinois to a 6 in. x 2 in. x 29 in. long slab using a 6000 pound steam hammer. After the forging was received at Argonne, 1/16 in. was scalped off of each 6 in. x 29 in. face and the slab was cut into two 6 in. x 2 in. x 14-1/2 in. sections. These were reduced at Argonne into sheet by rolling longitudinally at 700°C (lead pot furnace heated) to 0.230 in. x 6-3/8 in. x approximately 10 ft. long on a 16 in. x 24 in. two high United Mill with flat rolls and roller side guides at a rolling speed of 75 ft. per minute. Reductions were of the order of 5-10 per cent of the remaining thickness at each rolling stage. Reheating was done every fourth pass.

Because the available lead pot furnace would not accommodate the 10 ft. strips, subsequent reduction to final thickness was performed cold on a two high 16 in. x 24 in. United and a Bliss four high 5-3/4 in. x 12 in. x 16 in. mill, both equipped with guides to center the strip in the rolls. The strip was reduced 3 to 5 mils per pass with intermediate anneals after each 30-35 per cent reduction was accumulated. No furnace equipment was available to permit annealing an entire piece at one time, so that annealing was done by progressively immersing successive sections into a Pb tank furnace at 710°C for 5 minutes per section until the strip being annealed had been completely treated. Final dimensions of each strip after completion of cold rolling and a final anneal after rolling was completed was 0.065 - 0.066 in. thick x 6-3/8 in. wide x 32 ft. long. The hardness of the sheet was 81 R_B.

DECLASSIFIED

The size of the tube to be made was 1.780 in. O.D. x 0.065 in. wall as shown in Figure 2 which has a mean circumference of 5.385 in., a figure which would be the desired strip width except for shrinkage which occurs in forming and welding. This shrinkage factor is empirical in character, varying with desired diameter, intended wall thickness, and material characteristics. Ordinarily the shrinkage factor data is determined by experiment and compiled in chart form. Such experiments had not been run with zirconium because of a lack of material, so that an accurate correction factor was not available, and the factor developed for austenitic stainless steel was used. Although the use of this factor made doubtful achievement of the desired as-welded size, size was considered to be secondary to demonstration of the feasibility of the method. Once the correct factor was determined by this first run, it could be applied to subsequent lots.

Slitting of the strips was done at the Corey Steel Company in Cicero, Illinois. An error was made in slitting the first piece which was slit undersize to 5.385 in. instead of 5.485 in., but it was not scrapped because it could still be used as the leader strip to permit setting up of the tube mill and in the establishment of welding settings.

2. Rolling of Rib.

In order to produce a favorable welding current path the shape of the rib was altered from the final desired contour to a trapezoid having approximately 20 per cent greater cross sectional area than the final rail, the flat sides which would be re-formed to the ultimate form and welded at the same time. A roll (Figure 3) was made at Argonne to fit a small two high mill at the Corey Steel Company, whose facilities were used because of this particular mill for which rolls could be made easily and at nominal cost. Several rolling tests were run to determine the starting diameter which would best fill the form pass, and 0.226 in. appeared to be optimum. A number of attempts were made to roll the round rod directly to the shape in one pass, but the mill was too lightly constructed to prevent the rolls from opening. An intermediate roll flattening of the round to form a 0.300 in. wide x 0.116 in. rounded flat as shown in Figure 4 was performed on our 16 in. x 24 in. United mill, and it was possible to form this shape into the trapezoid in one pass, although a slightly better finish was obtained if the rolling was done in two passes, with the rolls opened a few mils for the first pass. It was found to be necessary to vapor blast the roll pass to prevent the stock from slipping in the pass during rolling causing the shape to roll considerably undersize in width. Actually, the shape never completely filled the pass at the base, always finishing approximately 30 mils narrower than the pass. Because the width was non-critical, this discrepancy was disregarded, especially when it was found that widths consistent within a few mils were repeatedly obtained.

DECLASSIFIED

3. Resistance Welding of Ribs to Tube Strip.

A 3 phase 200 KVA Sciaky Bros. seam welder, Model PMM. 2TDC-100-36-20 equipped with a brake to permit the use of intermittent drive (roll spot) was made available for this work which was done at the Sciaky plant in Clearing, Illinois, under the terms of a research contract between Sciaky Bros. and Argonne, which provides for the use of their tools and the assistance of their personnel.

The welding of the trapezoidal rails to the strip was planned to include forming of the rail and welding simultaneously, a fairly unique operation because of considerations of welding current distribution. The upper wheel, of Class I high conductivity Alkaloy A, was designed and machined at Argonne (see Figure 5) so that the female shaped contour exactly matched the finished contour of the final rib from the top of the rib to a point approximately 10 mils from the bottom. This was done by plunging an accurately ground form tool to its full depth, and then removing 10 mils from the outer diameter of the wheel. A 20 mil step was then machined into the contour as shown in Figure 5. This contour was developed so that the current would flow from the two spot contact between wheel and rail (see Figure 6) to the crown on the center of the bottom electrode, to start the weld, and forging some of the trapezoid out between the upper electrode and the sheet as the rail was heated to a temperature where it was plastic. The forged zirconium at the outer edges of the form and between the upper electrode and the sheet provided sufficient resistance so that the subsequent cycles of current necessary to complete the weld were adequately distributed across almost the entire rail to sheet interface, leaving only a few mils at the edges which had not reached fusion.

The bottom electrode (Figure 7) was machined with a 5 in. radius face to concentrate the welding heat (current) at the center of the weld section directly below the highest point of the rail. Low conductivity, Class III, Mallory 100 resistance welding alloy was used for this wheel so that the sheet temperature adjacent to the weld would be approximately of the same order as the rail temperature. The design and the maintenance of design tolerance of the electrodes, especially the upper wheel, is considered to be critical, having a direct effect on the location, extent, and quality of the weld.

The welding variables in resistance welding are interacting in nature and, after a few fundamentals have been applied, are generally determined by trial and error, judging the effectiveness of any particular group of settings by sectioning and microscopically examining the welded section. We were fortunate in having access to an excellent welder equipped with splendid controls over all of the welding variables, of which the following were considered to be critical:

1. Weld time (cycles)
2. Cool time (in.)

DECLASSIFIED

3. Motor speed (per cent of full speed)
4. Electrode pressure
5. Current (phase shift and vernier adjustment)
6. Motor rotation (time in cycles that wheels roll between welds)
7. Forging time (cycles)
8. Number of welding current impulses per welding cycle.

A series of experiments indicated that best welds were obtained with single impulse multiple cycle weld settings; single impulse, single cycle conditions required welding current of a high order, and metal expulsion occurred. Multiple impulse settings produced excessive surface temperatures which caused electrode pickup. This contaminated the work with the electrode material, and impaired the operating characteristics of the electrodes.

Electrode pressure affects contact resistance so that the latter varies inversely with pressure. The combined welding and forming operation required that the pressure be sufficient to form the zirconium when it was in a plastic condition but not at such a temperature that the forming electrode would weld to the work. In addition, fusion was necessary at the rail to strip interface. After a number of tests had been made, a pressure of 700 pounds, measured at the electrodes with a General Electric pressure gauge, was determined to be optimum under the conditions imposed by the other welding variables.

Table II, and Figures 8 and 9 list the weld settings, and include a current trace made of the weld setting made on a Brush recorder, and a schematic diagram of the welding cycle.

The welding of the rails required that the rails be accurately spaced and a fixture which would accurately position the rails in relation to the edge of the strip was designed and fabricated at Argonne (see Figure 10). This fixture permitted the components to be fed through it by the rolling electrodes without interfering with the rails which, being larger in area before welding, were reduced in area during welding and forming. An increase in length of the rail was thereby created which could not be satisfied in the direction of welding because of the restraint of the weld, but could be relieved by permitting the strip to move backward. An arrangement different from this was used in welding one rail on the first strip in which the rail was first located in relation to the strip edge, tack welded at locations throughout its length, and then seam welded. Because of longitudinal restraint the rail forged irregularly to the side so that the rail was rough and non-uniform in width. The second rail was welded on the first sheet using the improved fixture, and the weld and rail contour were excellent. Rail and sheet surfaces were fairly smooth after welding as indicated in Figures 11 and 12. Both rails were welded to the second thirty-foot strip in the same manner.

DECLASSIFIED

A photograph, Figure 13, of the welding arrangement shows the fixture in place at the machine with the upper and lower external water cooling pipes operating. In this view, the rib is welded to the strip at the left of the electrodes, and the rib is loose to the right of the electrodes. The operator is observing the welding, and while it appears that he is hand-feeding the rail to the electrodes, this is completely unnecessary as the operation can proceed automatically by locking the welding controls. As indicated in the photograph, the rails were welded one at a time, by first welding a rail to the strip, turning the strip 180°, and welding the other rail.

The welding electrodes, which were water cooled externally only, gave surprisingly good service, requiring no cleaning after welding ninety feet of rail.

A section taken through the weld shows complete fusion (Figure 14) throughout almost the entire interface.

After the resistance welding of the rails was completed, the two thirty-foot strips were inert arc butt welded together, and a six-foot long type 347 stainless steel leader was flash welded to a 4 in. section of zirconium which was later inert arc welded to the lead strip so that the tube mill could be threaded with stainless steel to conserve the precious zirconium. The zirconium to zirconium butt welds were made by hand in air using a helium cover gas. Table III is a compilation of the settings used in making the stainless steel to zirconium weld on a Thompson 75 KVA flash welder equipped with dual synchromatic push up. When all welding operations were completed the composite strip made up of two thirty-foot lengths of zirconium and a six-foot section of stainless steel was rolled into a coil approximately three feet in diameter to simplify shipping and handling at the mill.

B. Roll Forming, Welding, and Cold Finishing:

An arrangement was made with the Trent Tube Company at East Troy, Wisconsin, a manufacturer of high quality inert arc welded tubing, to permit the use of their personnel and facilities. Their mill is well equipped, having a number of tube mills of the type ordinarily made by the Yoder Company, a number of draw benches of various capacities, swaging machines, straightening tools, etc.

The forming and welding was done on a mill set up to form and weld a tube 1.780 in. O.D. by 0.065 in. wall, using rolls designed for stainless steel. Seven forming passes were used (Figure 15); the first three having the rolls working on both sides of the strip; the last three stages contacting the outer surfaces only. Clearance for the rails as shown in Items 1, 2, and 3 of Figure 15 was provided in the top rolls of the first three stands.

DECLASSIFIED

Although the weld between the stainless steel leader and the zirconium fractured badly in the first three stages, leaving only a small welded area to pull the sheet through the mill, forming of the strip was accomplished with very little difficulty after the rolls were set to compensate for the spring back of the zirconium. The tube as it entered the welding stage was not round, having flats at the outer diameter beneath the rails, and was slightly undersize. The latter could be easily corrected by adding extra width to the strip, and it is possible that changes in the forming rolls, or the use of strip in which the area beneath the rails was pre-formed with the correct curvature would reduce or eliminate the flattened sections on the outer diameter.

Helium, to protect the zirconium during welding, was fed at a flow rate of 13-15 liters per minute through the electrode holder to cover the W-electrode and the top of the melt. A gas box equipped with strips of woven quartz was integral with the electrode holder. The quartz strips were fitted closely to the tube surface to prevent ingress of air and loss of helium. The inside of the weld was also protected with a device which allowed helium to flow around the welded area. The effectiveness of this arrangement was indicated by the fact that the external weld surfaces, once optimum welding conditions were obtained, were almost fully bright with reaction colors only at the edges of the helium cover approximately $3/8$ in. from the weld center. The weld zone on the inside of the tube had not been as well protected and was covered with a dark film.

Welding and forming was done at a speed of the order of two feet per minute using a pure tungsten electrode and a welding current of 70 amperes at 15 volts supplied by a 40 volt Lincoln Electric motor generator rated at 300 amperes. The generator was run at full output, and the welding current limited to the above value by an external bank of resistors. The tube was connected as positive in the welding circuit.

Initial penetration was excessively heavy, and the weld was too wide so that the molten pool sagged excessively into the tube. This was gradually corrected as the first thirty-foot strip passed under the electrode, and the second thirty-feet was only slightly over-penetrated, having a weld slightly flat and $1/4$ in. wide on the top, with a drop-through of $1/32$ in. by $1/8$ in. wide. Over-penetration was deliberately resorted to in this work because of the small amount of material available, and the desire that the finished tubing have a weld of complete penetration. If more material had been available, complete penetration with only a few mils of drop-through could have been obtained. The avoidance of over-penetration is generally wise because the extra thickness of metal created at the weld when cold worked flat can propagate laps, cracks, and other defects. Figure 16 includes a photomicrograph taken at the junction of the fused zone and the basis material; and a macrophoto of the weld in the as-welded condition. If the macrophoto of the weld is examined closely, the dark reaction zones at the edges of the helium cover may be observed.

DECLASSIFIED

The tube as it came off of the mill was slightly twisted, was not straight, was under the intended size, and was not round. Figure 17 indicates the shape of the cross section and its dimensions at this stage.

It was believed that several cold working processes, namely, cold drawing, tube reducing, or swaging could be employed to round out the tube and finish the rails to the desired form. Because swaging was considered more feasible than cold drawing with its attendant lubrication problems, and Trent Tube does not have a tube reducer, a group of shaped swaging mandrels were designed by Mr. Joseph Olson of Trent and made at Argonne. These mandrels, shown in Figure 18, were designed with a ball on one end so that, when attached to a mandrel rod with a suitable holder, they were free to turn at will with the tube during swaging. When used in conjunction with long bearing (approximately 10 in.) swaging dies, it was believed that the tube would be improved in straightness and there would be a tendency to remove the twist from the ribs.

When the mandrels were ready for use, the first section of tubing which had been made from the strip which had been slit undersize to 5.385 in. and had one badly deformed rail welded to it, was cut into short lengths averaging about 5 ft. in length. The first short length, swaged in a power roll fed Aetna swaging machine over a 1.576 in. diameter mandrel in a 1.750 in. swaging die, was acceptably rounded, fairly straight, and had an outer diameter of 1.740 in. After swaging over the 1.592 in. diameter pin with a 1.750-1.800 in. contour die, again without any sign of effort by the Aetna swager, the rib contour remained excellent, and the outer diameter was expanded to 1.750 in. After several trials were run on short lengths to determine the most favorable swaging sequence, it became apparent that the swaging would be best done in two steps using first the 1.592 in. pin, followed by swaging over the 1.607 in. diameter mandrel, both operations being done in the same 1.750-1.800 in. contour die. Attempts were made to swage directly to 1.750 in. diameter over the 1.607 in. shaped pin, but the added thickness at the over-penetrated weld could not be worked at this rate without cracking. The length of tubing, 29 ft. 11-1/4 in. long, which had been made from the section of strip with the excellently seam welded rails was swaged according to the optimum schedule above. Its final dimensions were as follows:

Length	- 30 ft. 2-1/8 in.
Outside Diameter	- 1.744 in. - 1.750 in.
Wall Thickness	- 0.060 in. - 0.061 in.
Rail Twist	- Less than 1°
Rail Height	- 0.148 - 0.151

The shape of the rails (Figure 19) conformed exactly with the desired shape, blending perfectly with the inner diameter of the tube. This was true even with the badly deformed rail on the first section of the sheet. Very little change in hardness was caused by swaging as indicated in Figure 20 which includes hardness of the tube cross section at various stages.

DECLASSIFIED

After swaging the tubes were essentially straight, but not to within commercial tolerances. Straightening was attempted on several of the short sections using a roll straightener of the Medart type, but was discontinued when severe galling occurred between the zirconium tube and the aluminum bronze (Ampco) guide. It is possible, however, that this galling might be eliminated if a suitable lubricant were used.

Straightening was accomplished readily by hand straightening on a gag press equipped with round split dies made of a soft material similar to Kirksite.

The tubes were now considered to be complete and acceptable as an indication of the feasibility of the manufacturing process as proposed. That the process can make efficient use of the strip supplied is indicated by the fact that of the 60 ft. of strip fed to the mill, 52 ft.-10 in. was returned in the form of finished tubing. This entire amount could have been allowed to remain in one length, but for reasons previously explained, only one tube 30 ft. 2-1/8 in. (Figure 21) was left in one length, and the remainder was cut into four sections.

C. Testing of the Tubing:

1. Corrosion Tests.

The most popular corrosion test applied to zirconium is a high pressure-high temperature liquid water test using high purity water contained in stainless steel autoclaves. This test originated as a service simulating criterion for material intended for use.

Autoclave temperatures in the range 200°-315°C are used, although 315°C is the accepted testing temperature for the classification of zirconium into Grades I, II, or III. Only Grade I is considered as suitable for use in pressurized water reactors although other grades might be used in water cooled reactors which operate at temperatures below 250°C.

Because the material in the tube was originally classed as Grade III, and the tube was intended for service at a temperature of less than 200°C, the corrosion tests were run for 8 days at 200° and 250°C in water that had been distilled, deionized, degassed and contained in a stainless steel autoclave. The test conditions are listed in Table IV.

Only a thin superficial film developed on the sample in the test run at 200°C, indicating excellent corrosion resistance.

Two tests run at 250°C indicated that the areas of the samples on the back side of the weld, and those adjacent to the weld on top in one sample had become contaminated so that white corrosion products were formed during the corrosion test. The second sample run showed this effect

DECLASSIFIED

on the inside only, an indication that the external helium gas cover had been more effective in preventing atmospheric contamination. Figures 22 and 23 include photographs which show the corroded areas, and it is interesting to note that the corrosion has not involved the material in the cut edges immediately beneath the corrosion products which could signify that corrosion would not extend beyond the depth of the contamination, although this is open to question.

Based on these tests, the welded tubing was found to be resistant to corrosion in high purity water at 200°C. It is believed that material having satisfactory corrosion resistance at 250°C can be made if adequate helium shielding is employed during welding. The last statement is substantiated by corrosion tests made on a zirconium tube (smooth wall) made at an earlier date.

2. Physical Tests.

a. Leak Testing.

All of the lengths of tubing were tested for leaks by immersing the tubes in water while air pressure of 90 psi was maintained inside of the tubes. No leaks were observed.

After the air test had shown no leaks, the tubes were fitted with appropriate end fittings, evacuated, and examined for leaks with a General Electric mass spectrometer type helium sensitive leak detector. None were found.

b. Pressure Testing.

Before the finished tubes were shipped to Argonne, the Trent Tube Company tested them with water at 750 psi without damage to the tubing.

Several short lengths were prepared at Argonne to determine the ultimate pressure which the tubes were capable of withstanding, and the region of failure. This was done by capping the ends with rubber gasketed caps which were held tightly to the ends by clamping the sample in a tensile testing machine which compromised the test to some degree by imposing buckling loads on the tube wall. Pressure was applied to the inside with a hand hydraulic pump.

Two samples were run; one failed at 3600 psi; the second failed at 2900 psi, both failing at pressures of the order of 3770 psi, the calculated value based on Barlow's formula, $P = \frac{2 ST}{D}$, where P is the required pressure in psi; S is the allowable fiber stress which was 55,000 psi in this

DECLASSIFIED

case; T is the wall thickness (0.060 used); and D is the outside diameter (1.750 in.). Both failures occurred away from the weld in the heat affected area (Figure 24) in a location where the over-penetrated weld had been swaged to form a very shallow fold, thus creating a stress raiser. The possible effects of over-penetration and the reasons for its existence in this lot of tubing have been discussed previously, and the elimination of this condition is quite simple. The pressure tests are evidence that the welded tubing is sufficiently strong for the intended reactor use, and that the weld is as strong as other areas of the tubing.

c. Crush Tests.

Several short sections were crush tested in accordance with ASTM procedure A83-52T by squeezing the samples under column loading between the platens of a Riehle hydraulic powered universal testing machine.

All samples were satisfactory and were compressed more than 10 per cent of their length before any splits were observable in the tube walls, all such failures occurring first in locations away from the inert arc weld. A photograph of one of the crush test samples after testing is included in Figure 25.

d. Flare Tests.

The procedure outlined in ASTM Specification A83-52T was followed in testing a small number of specimens taken from one of the short lengths of tubing. In short, this test involves pressing a tapered punch into the open end of a right cylinder sample of tubing to form a flange or flare on the tubing. The response of the sample to this test indicates whether the tubing is flareable, and also delineates the areas which fail first whether because of local defects, or the exceeding of allowable stresses. The latter aspect of the test was the desired object. The flare was taken to the point where the punch had been pressed tightly to the die, and not extended beyond this to a right angle flange. Actual failure did not occur in any of the samples, but necked down areas developed adjacent to the inert arc weld at the stress raiser previously mentioned. One of the flared samples is shown in Figure 25, and the fold next to the weld which was formed by swaging the over-penetrated weld is clearly visible.

IV. CONCLUSIONS:

1. Hanford type process tube can be fabricated from zirconium strip by welding shaped rails to the strip followed by roll forming and inert arc welding, finishing after welding by cold swaging over a shaped mandrel.

DECLASSIFIED

2. Tube length is limited only by the length of the starting strip which can be made by the method outlined above.

3. Good control of required dimensions within commercially acceptable tolerances may be obtained, although some qualification should be made in respect to dimensions because of the limited production experience on which it is based. Approximately fifty feet of this shape have been made, all in one run, in which one length of tube finished at thirty feet, and no abnormal difficulty was encountered.

4. The process is made up of several steps, no one of which is unduly complicated or expensive, and it is believed to be competitive on a cost basis with other processes.

5. Fairly high production rates are possible. Welding of the rail to the strip and inert arc welding of the tube can be done at rates of the order of two feet per minute. Rolling of strip and rail, and the slitting of tube strip are comparable to steel practice.

6. Shipment of strip to the tube mill may be done in loosely coiled form without adverse effect. Shipment of the finished tube, approximately forty-two feet long, which is not related to manufacturing method, is the only shipping problem, and that has been effectively solved for a number of years.

7. All work was done on Grade III arc melted crystal bar material which has excellent ductility, although no great difficulty would be anticipated from Bureau of Mines consumable electrode arc melted stock. The expected good response of Bureau of Mines zirconium is a personal opinion based on previous experience, and it would be appropriate that a pilot run of tubing be made of this material before any large quantities are made.

REFERENCE

1. ANL-5138 R. A. Noland, D. E. Walker, R. E. Macherey: Preliminary Investigation to Determine the Feasibility of Manufacturing Zirconium Tubing by Roll Forming and Inert Arc Welding.

DECLASSIFIED

FIGURE 1

CROSS SECTION OF AL HANFORD PROCESS TUBE

DECLASSIFIED

Table I

TYPICAL PHYSICAL AND MECHANICAL PROPERTIES OF
ALUMINUM vs. ZIRCONIUM *

	Aluminum		Crystal Bar Zirconium
	2S	63S	
Approximate Melting Range °C	645-660 ⁽¹⁾	615-650 ⁽¹⁾	1845 ± 25° ⁽¹⁾
Density gm/cm ³ (20°C)	2.70 ⁽¹⁾	---	6.50 ⁽¹⁾
Electrical Resistivity μ ohm-cm (20°C)	2.66 ⁽¹⁾	---	42 ⁽¹⁾
Thermal Conductivity, (Room Temp.) cal/(sec)(cm)(°C)	0.503 ⁽¹⁾	---	0.052 ⁽¹⁾
Ultimate Tensile Strength, P.S.I.	13,000 ⁽²⁾	22,000 ⁽²⁾	59,600 ⁽³⁾
Yield Strength, P.S.I.	5,000 ⁽²⁾	13,000 ⁽²⁾	53,000 ⁽³⁾
Elongation, (% in 2 in.)	45 ⁽²⁾	28 ⁽²⁾	21.9 ⁽³⁾
Hardness (Rock. B)	77 ⁽⁴⁾	102 ⁽⁴⁾	81 ^{(3) (4)}

*At room temperature

(1) The Reactor Handbook, Volume 3, used as reference.

(2) The Aluminum Company of America Handbook used as reference.

(3) All results determined on Arc Melted Crystal Bar Zirconium, at Argonne.

(4) Readings taken in as-rolled and annealed condition.

FIGURE 2

CROSS SECTION OF INTENDED ZR PROCESS TUBE

DECLASSIFIED

FIGURE 3
RIB FORMING ROLL

FIGURE 4

FORMING STAGES USED IN ROLLING SLUG RAILS

FIRST STAGE—ZR ROD

SECOND STAGE—ROD ROLL FLATTENED

THIRD STAGE—ROLL FORMED RIB PRIOR TO WELDING

DECLASSIFIED

FIGURE 5
WELDING WHEEL ELECTRODE

MATERIAL	COPPER
CLASS	T-AL-KALLOY A
TYPE	HIGH COND.
HARDNESS	Rb 3-20

SECTION-UPPER WHEEL

DECLASSIFIED

FIGURE 6
SCHEMATIC SECTION OF RIBBED FLAT SHOWING RIB WELDING GEOMETRY

RIB BEFORE WELDING

RIB AFTER WELDING

FIGURE 7
WELDING WHEEL ELECTRODE

MATERIAL	COPPER
CLASS	3MALLORY 100
TYPE	LOW COND.
HARDNESS	Rb 90

DECLASSIFIED

Table II

**MACHINE SETTINGS AND OTHER CONDITIONS
EMPLOYED ON SEAM WELDING OF Zr RIB**

Heat Time (cycles)	9
Cool Time (cycles)	2
Wheel Pressure	700 lbs.
Phase Shift	30 Major 86 Vernier (120,000 amps. max.)
Weld Time (cycles)	1
Motor Rotation (cycles)	9
Forge Time (cycles)	2
Impulses	1
Spots/in.	10
Welding Speed (in./min.)	20-1/2
Cooling	External Water
Type of Welding	Intermittent Seam
Forging Pressure	700 lbs.

DECLASSIFIED

FIGURE 8

TRACE OF WELDING CURRENT MADE DURING
RESISTANCE WELDING OF RIB USING
BRUSH OSCILLOGRAPH

DECLASSIFIED

FIGURE 9

GRAPHICAL RELATIONSHIP OF ELECTRODE FORCE VS. SECONDARY CURRENT

SINGLE IMPULSE-NO CURRENT DECAY-INTERMITTENT DRIVE-FORGE TIME

FIGURE 11

Photographs of ribbed strip prior to tube forming
showing weld pattern and general smoothness of rib.

RIBBED STRIP TOP VIEW

14,315

1X

FIGURE 12

RIBBED STRIP BOTTOM VIEW

14,316

1X

DECLASSIFIED

FIGURE 13

Rib seam welding arrangement showing the fixture in place at the machine with the upper and lower external water cooling pipes operating.

14,523

1X

DECLASSIFIED

FIGURE 14

Macro photograph of rib to sheet resistance weld.

14,352

7X

Photomicrograph of rib to sheet resistance weld
taken in center of weld.

13,989

250X

DECLASSIFIED

Table III

MACHINE SETTINGS USED TO MAKE BUTT WELD OF STAINLESS
STEEL LEADER TO RIBBED Zr SHEET ON FLASH WELDER

Materials		Die Material		Initial Die Opening (inches)	Final Die Opening (inches)	Work Overhang (inches)		Flash Off (inches)
Right	Left	Right	Left			Right	Left	
Zr	Stain- less Steel	Cu	Steel	11/32	3/16	3/32	1/4	3/32

Amount of Upset (inches)	Forge Delay (cycles)	Upset Pressure (lbs.)		Current Cutout (inches)	Flashing Speed	Transformer Tap No.	Clamp Pressure (lbs.)
		Initial	Final				
1/16	6 B.C.C. (1)	40	100	1/64 A.S.O.U. (2)	3.5	H 8 (3)	100

(1) B.C.C. = Before Current Cutoff.

(2) A.S.O.U. = At Start Of Upset.

(3) H = High Heat Range With the Transformer Connected in Parallel.

FIGURE 15
FORMING STAGES EMPLOYED IN ROLL FORMING
INTERNALLY RIBBED ZR TUBE

DECLASSIFIED

FIGURE 16

Photograph of tube section shown after welding but before swaging, indicating general smoothness of welds and irregular contour of tube.

14,351

1X

Photomicrograph of inert arc weld in zirconium tube taken at junction between fused and parent metal.

14,370

100X

DECLASSIFIED

FIGURE 17
CROSS SECTION OF WELDED TUBE
AS WELDED AND AS SWAGED

TUBE AFTER WELDING

TUBE AFTER SWAGING

DECLASSIFIED

FIGURE 18

SHAPED SWAGING MANDREL

1	1.562 Outside Diameter
2	1.577 " "
3	1.592 " "
4	1.603 " "
C to D Hardened to Rc 61-63	
B to C Redrawn to Rc 35-45

FIGURE 19

Photograph showing rib shape after resistance weld, tube and rib contour after roll forming and finished tube after swaging.

14,314

1X

DECLASSIFIED

FIGURE 20
ZR HARDNESS TAKEN AT VARIOUS STAGES
OF MANUFACTURE OF TUBE

RIBBED SHEET

TUBE AFTER WELDING

TUBE AFTER SWAGING

Readings Taken on Vickers Testing Machine
and Converted to Rockwell B Scale

DECLASSIFIED

FIGURE 21

Photograph of longest length of finished tube 30' 2-1/8".

ANL 106-1078

DECLASSIFIED

Table IV

CORROSION TABLE

Sample No.	Temp. °C	Time (Days)	Water PH		Weight Change	Comments
			Start	Finish		
1	250	7.3	7.1 - 400 K ⁽¹⁾	6.7 - 100 K	-1.0 mg - 33 cm ² area	Lustrous irridescent coating; white film on outside welded edges and covering inside weld.
2	200	8	6.7 - 500 K	6.7 - 180 K	+0.2 mg - 6 cm ² area	Overall color dark gold. Gray line on interior welded edges only.
3	250	8	6.7 - 500 K	6.3 - 120 K	+0.9 mg - 6 cm ² area	Overall light gold color. White film covering most of inside weld and slight white line at edges of outside weld.

(1)K = Electrical Resistivity of water in ohms. (500 K = 500,000 ohms).

Samples prepared by etching in 5% (by volume of 52 w/%) HF followed by a quick dip in HNO₃

FIGURE 22

Outside view of tube section after 73 days exposure to 250°C water.

14,354

Sample I

1X

Appearance of inside of tube section after 73 days exposure to 250 C water.

14,359

Sample I

1X

DECLASSIFIED

FIGURE 23

Photographs of samples removed from inert arc welded zirconium tube after corrosion testing in high temperature water.

14,529

1X

Sample II
After 8 days in 200°C water.

14,528

1X

Sample III
After 8 days in 250°C water.

DECLASSIFIED

FIGURE 24

Photograph of section of inert arc welded tube deliberately ruptured during pressure testing.

PRESSURE TEST

14,486

1X

DECLASSIFIED

FIGURE 25

Photographs of flare and crush test specimens after completion of tests.

FLARE TEST

14,485

1X

14,487

1X

DECLASSIFIED