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Argonne National Laboratory

DEVELOPMENT OF ZIRCONIUM CLAD URANIUM PLATES FOR REACTOR FUEL

by

J. J. Lawless, C. H. Bean, J. R. Wooland,
and R. E. Macherey

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FOR REACTOR FUEL

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DEVELOPMENT OF ZIRCONIUM CLAD URANIUM PLATES FOR REACTOR FUEL

I. INTRODUCTION

The objective of the zirconium-uranium cladding program at Argonne National Laboratory has been to develop methods for manufacturing Zrclad uranium plate in shapes and sizes suitable for reactor fuel. The course of the investigation was unlimited by specifications on the end product. However, general goals such as high bond strength, impervious cladding, and good dimensional tolerances were kept in mind. Every effort was made to simplify designs and processing operations. To establish a billet design and processing operation it was necessary to understand the effect of contamination on the bonding surfaces, and to determine the most desirable shape of billet section.

II. SUMMARY

In this investigation a method has been developed for production of Zrclad uranium plate based upon previous investigations at Argonne and Oak Ridge National Laboratories, and preliminary investigations in the present work. The present preliminary investigations included experimental studies of the effect of interface atmosphere upon roll bonding and led to the conclusion that thin layers of air between bonding surfaces could be tolerated. It was also determined experimentally that rectangular shaped billets rolled in flat rolls were most promising for production of plates with good dimensional characteristics. A method of billet manufacture was devised in which the core and jacket parts were assembled, pressed together to minimize the amount of air at the core-jacket interface, and all jacket seams welded while under pressure. The billet was then sheathed in a steel can for protection of the zirconium jacket during hot rolling. Several canning steels were tested, and it was found that steel containing a gas stabilizing alloy such as titanium had the least affect on the ductility of the cladding. Various rolling temperatures were studied and different combinations may be recommended depending upon the properties desired in the finished plate. Results of a considerable amount of testing show that the original microstructure of the core material will have a significant effect on cladding uniformity, and points up the requirement for well-designed rolling equipment and skillful operation if plates with close dimensional tolerances are to be produced.

Exploratory work with uranium-zirconium alloy core material was encouraging. It may be possible to develop an alpha rolling procedure which will produce very uniform cladding because the alloy is apparently much more resistant to deformation in this temperature range, and should be

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inherently finer grained. Exploratory work with zirconium-tin (3 w/o Sn) cladding was discouraging, and a fresh approach has been recommended. The principal difficulties with tin alloy seem to be susceptibility to tearing of the cladding under heavy reduction, and reluctance of the cladding to bond to the picture-frame edges at ordinary rolling temperatures.

III. CONCLUSIONS

It has been established that the production of Zrclad strips or plates of uranium is feasible. Specifications imposed by a particular design would dictate selection of the exact conditions of the manufacturing process.

Dimensional tolerances for modified picture-frame plates of the following order should be possible:

Width tolerance;	$\pm 0.030''$ in the width range of 2" to 5" .
Thickness tolerance;	$< \pm 0.001''$ in the thickness range of 0.050" to 0.250".
Straightness;	less than $1/8''$ camber in 10'.
Cladding thickness;	$\pm 20\%$ on 0.010" cladding.
Bonding	(estimate 99% of surface area).

Cladding thickness variation is an inherent weakness of any process requiring high total reductions in rolling. It is considered likely that the variation in cladding thickness is related to grain size and orientation of opposing dissimilar grains at the interface. Plates from billets with beta heat-treated normal uranium cores rolled in the alpha temperature range showed minimum cladding thickness variation. Plates rolled in both gamma and alpha temperature ranges showed maximum variation. Combination gamma and alpha rolling is thought to produce a more reliable bond. Simulated service tests would be required for full evaluation of serviceability of either alpha or combination rolled plates.

Assuming that a satisfactory method of sealing plate ends by welding can be developed, plates can be produced which will be impervious to water under the conditions of the corrosion tests which have been performed. Corrosion resistance of the cladding itself should be consistent with the grade of zirconium selected. About 0.006" of cladding is probably the minimum safe average cladding thickness for service of the type represented by corrosion testing reported here. More intensive testing may indicate that heavier clads are required for positive continuous protection of the core from water leakages. When fission product retention is the sole function of the cladding, thinner clads can be supplied, perhaps 0.004" if end sealing is not required.

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It is fairly evident that zirconium clad plate resists bond failure which might result from stresses induced by dimensional changes up to 2% of the original dimensions, as indicated by thermal cycling results. Purely mechanical tests of the best bonds also indicated probable strengths in the range of 30-50,000 psi.

There is much current interest in uranium-zirconium core alloy for dimensional stability and zirconium alloy (as Zr-Sn) cladding for increased corrosion resistance. The application of cladding techniques developed in this investigation to the alloy cladding and core materials will require some variations. Feasibility seems to be indicated for uranium-zirconium cores. Feasibility of zirconium-tin cladding must be established by further investigation.

IV. RECOMMENDATIONS

The following subjects are recommended if further investigation of the cladding problem is to be undertaken:

- a. End Seals: Develop a procedure for closing the ends of plates of the type described in this report, which have been trimmed, exposing the core. Welding methods employing inert gas shielded arc, and automatic resistance welding would seem to be logical choices.
- b. Cast Billets: It would appear that cladding billets could be cast with attention to alloying, cooling rate, and heat treatments to produce fine grain core material. Subsequent rolling should then develop reasonable clad uniformity. Rectangular or square castings would be desirable for production of accurate widths of plate.
- c. Uranium-Zirconium Alloy Cores: Production of clad plates with alloy cores could proceed along lines similar to those followed in the present investigation, but it would seem even more desirable to explore the possibility of combining the use of alloy with experimental work on a cast billet technique.
- d. Zirconium-Tin Alloy Cladding: The use of zirconium-tin and similar corrosion resistant alloys for cladding is probably the most doubtful of the important remaining problems. In the exploratory work done with 3% Sn alloy considerable irregularity of cladding thickness was observed, and the production of satisfactory seals at the plate edges was not attained. Fresh consideration of the entire alloy cladding problem is advisable.

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V. BILLET DESIGN AND ROLL CLADDING PROCESS

1. Preliminary Experiments

At the beginning of this work, the conditions necessary for the successful bonding of zirconium to uranium were not known and a few preliminary experiments were performed to determine feasibility of roll bonding.

A number of electropolished uranium plates, 4" x 6", were enclosed in cleaned zirconium picture-frames and cover plates and heliarc welded. The welded assembly was similarly enclosed in a steel envelope which was also welded. The assembled sandwiches were 7-1/4" x 5-1/4" x 0.625" in outside dimensions. The sandwiches were hot rolled at various temperatures and reductions.

After hot rolling, the steel jacket was pickled off. A test specimen, approximately 2" x 6" x 0.088", was cut from the center section of each roll clad plate and subjected to a bend test. The bend test consisted in gripping the specimen in a vise and bending it in one direction until failure occurred. The fracture was examined and classed as: 1) satisfactory if the clad broke even with the core material (Figure 1a); 2) unsatisfactory if the cladding separated from the core (Figure 1b).

The hot rolling schedule which produced the best zirconium-uranium bond is given in Table I. The first reduction pass was taken with the uranium core in the gamma phase, in subsequent passes the uranium was in the high alpha region. These experiments demonstrated that it was possible to establish a good bond between zirconium and uranium by hot rolling, further work was concerned with improved billet design and refinement of the rolling procedure.

2. Effect of Billet Atmosphere on Bonding

It has been brought out by previous investigators¹ that oil, water, or dirt films on surfaces to be bonded, prevent metal to metal contact and inhibit bonding. Furthermore, the presence of active gases at the interface, particularly air which forms oxides and nitrides, is undesirable. Unfortunately, these contaminants can never be completely avoided in the preparation of metal surfaces.

Rather than attempt to attain perfection in surface preparation, it would be more practical in the manufacture of large plates, to tolerate a certain amount of contamination on the billet interfaces, and to attenuate its effect by resorting to extensive reduction by rolling, or by diffusion of the contaminants into the base or clad metal. The most advantageous compromise between the degree of interface cleanliness, and the degree of

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attenuation would be difficult to determine. For the purposes of this investigation it seemed sufficient to establish an approximate limit of interface contamination for an arbitrary billet design. A preliminary series of billets were processed for this purpose. The billet consisted of an uranium core $1\frac{3}{4}'' \times 5'' \times 1''$, enclosed in a zirconium jacket which was assembled about the core without welding - except as noted. The billet was then placed in a steel can for protection of the zirconium during heating as shown in Figure 2. The design of these billets was based upon a proposed reduction of 90% in rolling. The 90% reduction was selected arbitrarily to minimize machining requirements, and because the resulting billet was of convenient size for heating in available equipment. Low carbon (C-1020) steel was specified for the cans, Grade III arc-melted crystal bar for the jackets, and vacuum induction melted uranium for the cores. All of the billet surfaces were carefully cleaned and the parts assembled in the can. The can was closed and connected by means of a $\frac{3}{8}''$ I.D. tube to a vacuum system capable of producing a vacuum of 10^{-5} mm. A vacuum gage was fitted to the opposite end of the can to indicate the billet pressure. The billets were evacuated to various degrees, heated to rolling temperature, cooled, opened, and examined for contamination of the metal surfaces.

Results from this series of billets are given in Table II. Billet #1, which was evacuated but not outgassed before sealing, developed considerable scale on the metal surfaces during heating. Outgasses from the steel can were probably responsible for the scale. Billet #3 was evacuated and outgassed during heating. Subsequent heating did not develop noticeable contamination. It is worth noting that the increased interface spacing, 0.008" to 0.030" - Billet #1 and Billet #3, respectively, improved the evacuation rate without heating. However, 72 hours were required for evacuation during heating for outgassing. Since the uranium was melted and cast in vacuum, and the zirconium in inert atmosphere, the steel in the can was the only likely source of the amount of outgassing indicated by the pressure measurements and surface contamination. The steel can material in Billet #13 was vacuum annealed for 6 hours at 800°C before assembling. The time required to evacuate the billet, canned in this steel, to 200 microns pressure at 800°C is only 3 hours compared with 3 days for Billet #3.

Billet #2 was assembled without evacuation. This billet was made by welding a zirconium box and inserting a close fitting polished uranium core. The box was closed by welding a cover on the open end. It was assumed that this arrangement resulted in a sufficient seal to prevent outgasses from the can reaching the bond interfaces and forming contamination. The estimated 0.004" thick layer of air entrapped in the billet would be the only source of contamination to interfere with bonding. After heating the billet was opened and inspected. The zirconium surfaces were clean and bright but the uranium was uniformly coated with a very thin layer of gray powder, sufficient to be noticeable on the tip of the finger after wiping the core from end to end. It was observed that the amount of contamination developed in the unevacuated sealed billet was not significantly greater than that developed in the evacuated Billet #13.

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Billets #5 and #6, duplicates of the unevacuated Billet #2 and the evacuated Billet #13, respectively, were assembled for rolling. These billets were rolled under identical conditions and the plates were tested. Metallography and bending tests indicated that bonding between zirconium and uranium had been obtained in both plates. In corrosion testing, the plate from the unevacuated Billet #5 survived 286 hours of exposure in water at 250°C. The plate from the evacuated Billet #6 failed at the Zr-Zr bonds at the plate edges in less than 24 hours at 170°C.

It was concluded that further improvement of the evacuation procedure would require gas free steel for cans, or evacuation of the zirconium jacket after sealing. Further development of a cladding process without billet evacuation seemed to be justified. Such a process offers a promising method of producing serviceable plates with a minimum of development and manufacturing problems.

3. Investigation of Billet Shapes

In order to facilitate bonding without prior evacuation, the minimum practical interface spacing in the billet is required regardless of the design selected. This requirement had an influence on billet design. Two billet shapes were suggested by previous investigations of Zrcladding, and still seemed to offer the most promise; that is, rectangular sections as in picture-frame and sandwich billets, or cylindrical billets.

Cylindrical billets shown in Figure 3 have the advantage of extreme simplicity of assembly. Welded tubes were used for both the steel can and the zirconium jacket, and the cores were made by machining and pressing into the zirconium jacket. Zirconium plugs were fitted into the ends and welded, and the fabricated jacket and core assembled into a steel can. A fundamental objection to the cylindrical billet seemed to be the poor probability of obtaining a bond near the edges of the plate; however, variations on conventional flat rolling of cylindrical billets seemed to promise some advantages.

A series of exploratory cylindrical billets were assembled for rolling. The first of these billets was rolled directly to a flat plate. In Figure 4b, we show schematically the progress of the reduction which is straight-forward. It may be noted that the spread is considerable, amounting to about 50% of the original diameter. Examination of the cladding on one plate rolled directly to a flat confirmed the suspicion that bonding would not be obtained near the edges of the plate. Distribution of cladding on this plate is shown in Figure 5.

In order to initiate bonding in those locations on the billet which upon final rolling would become the edge of the finished plate, several billets were rolled in open-square passes, and several in oval-edge oval sequence of passes as shown in Figures 4c and 4d. Both of these procedures resulted in plates bonded all the way around the section, as judged on the basis of metallographic

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examination. In the case of the square passes however it was found that the corners were pinched and that the cladding on the flat sides was extremely irregular in thickness as shown in Figures 6 and 7. Cladding thickness irregularities persist through flat rolling (see Figure 8). In the case of oval-edge oval procedure, it was found that irregularities in cladding thickness existed around the entire perimeter of the core. Considerable difficulty was encountered in attempts to develop oval-edge oval reductions which would not overfill the passes during rolling.

Flat or picture-frame billets require more parts than cylindrical billets, and it was felt that billet fabrication would be proportionately more complicated. The problems resulting from complex design however could be resolved in production. Referring to Figure 4 it will be noted that the spread resulting from rolling cylindrical billets to plate is greater than for rectangular billets. The rectangular sections can be flat rolled quite accurately, and by variation of the can design and rolling procedure it is possible to reduce lateral spread in rolling to a very low value.

In Figure 9 are shown the two types of cans which were used in this investigation. From study of the plate widths produced in these designs it is apparent that the two-piece can of Figure 9b is superior in restraining spread. Cans were removed from the hot rolled billets by either shearing the edges off and separating the balance of the can, or by pickling the can off with dilute nitric acid. Neither of the can designs used presented a problem in decanning. Figure 10 shows a typical decanning operation in which the ends and edges of a hot rolled billet were sheared to remove the weld, and the steel cover plates removed to expose the Zrclad uranium plate.

4. Billet Assembly Method

For the first 15 flat billets produced in this investigation, the billet parts were machined to a specified tolerance. The zirconium jacket was clamped around a dummy core and the joints welded with an inert-gas shielded arc without filler metal. A uranium core was then substituted for the dummy core, the billet was closed, seal welded, and put into a steel can. The principal disadvantage of this technique was the requirement for precision machine work, if only reasonable quantities of gas were to be entrapped in the sealed billet. It was estimated that billets assembled by the welded box technique would result in a minimum inclusion of 0.0025 cubic inches of air per square inch of interface. On the basis of the preliminary experiments to evaluate contamination, it was felt that improved bonding would have been obtained if smaller volumes of air could be enclosed in the billet. It was also considered desirable to develop a less complex fabrication method.

Accordingly, an alternate method of billet assembly was devised to minimize the air gap between core and cladding. The uranium core and zirconium end plugs were machined to tolerances of ± 0.005 ", and the zirconium covers and sides were sheared from cold finished zirconium sheet.

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Billet components are shown in Figure 11. The zirconium parts were then assembled about the uranium with the ends and sides clamped tightly against the core.

The assembled billet was placed in a hydraulic press with water cooled copper plates in contact with the billet covers as shown in Figure 12. Pressure on the billet during assembly was held at 2 tons or more per square inch. As pressure was increased on the assembly the zirconium cover plates deform to conform to the surfaces of the core, end plugs, and sides. While under pressure the billet joints were welded with an inert-gas shielded arc to seal the billet. Cooling of the billet surfaces with chill plates reduced the extent of heat effect in contaminating the interfaces at the edges and also reduces contamination of the weld metal. Contamination of the weld metal is of considerable importance from the standpoint of corrosion.

5. Billet Processing

A considerable amount of data on rolling variables has been collected, as shown in Tables III and IV. All of the processing variables affect one another, and affect several of the characteristics of the finished plate. Consequently accurate selection of specifications for processing would require a great deal more data than is given here. However, some approximate specifications have been formed, and a flowsheet for the visualized operations is given in Figure 13. Testing results given in Section VII of this report established that bonded cladding can be obtained by rolling the billet with a 90% reduction at 635°C. A preliminary 25% reduction at 840°C followed by reduction to a total of 90% at 630°C also develops a bond. It has not been possible to reliably measure the absolute strength of bonds produced, but it is believed that the combination rolling produces stronger bonds.

Study of a number of plates rolled by the processes outlined in the preceding paragraphs, indicates that variation of rolling speed, rolling temperature, roll diameter, etc. result in reduction effects similar to effects observed in conventional rolling processes. However, cladding thickness varied significantly. Since the variables that affect cladding thickness were not understood, it was considered worthwhile to expend some effort in an attempt to isolate these variables.

A series of exploratory billets were rolled to various partial reductions to determine at what stage in processing the cladding thickness variations originated. Cladding distributions for billets rolled to a reduction of 30% and 55% in the gamma temperature range are shown in Figure 14a and 14b. The maximum deviation from average thickness is about 14% and 10%, respectively. A billet rolled to 30% reduction in the gamma temperature range plus additional reduction to a total of 75% in the alpha temperature range had a maximum deviation of 23% from average cladding thickness as shown in Figure 14c. These results seem to indicate that wide variations in cladding thickness were initiated during the alpha rolling.

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The crystal structures of uranium and zirconium provide preferred planes and directions in which deformation occurs in each grain. A material with coarse, randomly oriented grains, would be expected to show a tendency for variable yielding of the surfaces under uniform pressure. The use of fine grain material could be expected to overcome some of the localized deformation of the cladding at the interface. Fine grain size in the zirconium would be obtained by working the ingots severely. Since the zirconium for this investigation was made from 6" diameter ingots worked to sheets 7" wide x 1/8" thick, about 25-1 reduction, it was assumed that this material would be sufficiently refined. A 3" x 3" ingot was the maximum size of uranium ingot available for this work, permitting only limited working of the core material before assembly into the cladding billet. The maximum reduction to produce a 2" x 1" x 5" core was about 60%. However, study of cladding thickness of plates rolled from billets with core material previously reduced 60% as compared with those in which the core material had no previous reduction showed no improvement in uniformity of cladding thickness (see Billets 65 and 66 in Table V).

A number of billets were fabricated with beta heat treated cores. If such billets are rolled by the combination gamma-alpha procedure, no improvement in cladding uniformity was obtained (see Billets 72 and 73 in Table V). Another set of billets containing beta treated cores were rolled in the alpha temperature range only. Results of measurements on these plates indicated a statistical improvement in cladding uniformity. Table VI shows that beta heat treated cores have an average variation, (V_A), of cladding thickness of 0.62 mils as compared to 1.15 mils for alpha or alpha-gamma rolled core material without heat treatment (see Tables V and VII).

Another source of cladding variation might be hardness variation of the zirconium, uranium, or the steel can at the rolling temperature resulting from variable alloy or residual impurities in the metals. cursory examination of hardness near the interface of clad plate samples indicated a possible correlation between hardness and cladding variation. Further investigations along these lines are justified; however, a comparison of cladding uniformity of plates made with virgin metal cores, (nominally 50 ppm carbon), and remelted U slugs for cores, (nominally 500 ppm carbon) shows no important differences (see Table VIII). Alloy cores (such as uranium - 2 w/o zirconium), might have sufficient hot hardness to reduce cladding irregularities. However, the use of beta heat treated cores with alpha phase rolling seems to be the best proven solution to the cladding uniformity problem.

The ultimate specification of bond strength, and cladding uniformity will have to take account of the fact that alpha rolling (with beta treated cores), does not produce the highest strength bonds. Combination gamma-alpha rolling provides good bonds but also produces large variations in cladding thickness.

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6. Finishing Methods

Clad plates rolled hot in steel cans can be produced with surface quality and dimensions somewhat less uniform than by most commercial hot-rolling processes. For reasonably precise assemblies of clad plate it will be necessary to improve the dimensions of the hot rolled plate by some type of finishing operation. Cold rolling in a 4-high mill is practical, but cold reductions should be limited to 10 or 15%. Reductions above 30% cause separation of the zirconium jacket and uranium core along the edges of the plate.

Consideration of hot finishing methods leads to speculation on methods of processing in which the can might be removed as soon as bonding is initiated, (after 75 to 80% reduction for instance), followed by low temperature finishing. Samples of plate have been rolled at 300°C with over 50% reduction and at 600°C with over 60% reduction. The finishes resulting from these processes were good and the plates were free of edge cracks. Measurement of cladding thickness and analysis of the results indicates that finish rolling has very little effect on the uniformity of cladding (see Table IX).

7. Zrclad Uranium-Zirconium (2 w/o Zr)

In view of the considerable interest in stabilized uranium-zirconium alloy as a reactor fuel, some consideration has been given to the problem of cladding this material. The data obtained in this investigation are not sufficient to form a basis for specifying a process. However, the results are encouraging, and further work is recommended.

Three billets were prepared by the press-assembly technique and rolled to a 90% reduction at various temperatures. The core alloy was arc-melted and the zirconium content ranged from 1.79 w/o to 3.03 w/o Zr in six locations, and 10.8 w/o at the very top. The segregation was noted in microstudy of one finished plate. Data given in Table X indicate that the combination of gamma-alpha rolling temperatures will give the best results with respect to bonding. Excessive rolling (75% reduction) in the gamma phase results in extrusion of the core through the jacket. Alpha rolled alloy plates had pimples cladding, and small (1/16" diameter) unbonded areas existed under the pimples. The occurrence of pimples is probably related to entrapped or dissolved gas in the arc-melted alloy. Further investigation of low temperature bonding of alloy plates is justified if vacuum melted alloy can be used.

8. Zirconium-3 w/o Tin Alloy as Cladding Material

A series of 6 billets were fabricated to explore the feasibility of cladding uranium with a zirconium-tin alloy, using flat billets assembled in press welded modified picture-frames. The only material which was

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available for this investigation was a Bureau of Mines graphite melted alloy billet, No. S-4044 Sn having the following composition:

Sn	3.16 %
Fe	1100 ppm
N ₂	70 ppm
C	2450 ppm
Zr	Balance

All billets were assembled in sealed C-1020 steel cans for rolling except No. 47 which was heated in a helium atmosphere and rolled bare. Variations were made in rolling temperature, reduction per pass, and passes per reheat in an attempt to develop a rolling procedure which would result in uniformly clad plates with satisfactory bonds. The cladding material used with 2 billets was vacuum annealed 1 hour at 1000°C. Details of rolling procedure are contained in Table XI.

Finished plates were measured and examined for conformity and surface defects. The core distribution was determined from autoradiographs and the cladding thickness was measured across the width at 0.10" intervals from sections of each plate. Evaluation of bonds at the plate edges and clad to core interface were made from metallographic examinations and destructive tests.

Billets which were rolled in steel cans were uniform in thickness and width. No. 47, which was rolled bare, ruptured at one of the jacket welds on the first pass of 5% reduction at 840°C. No attempt was made to reseal this billet. The surfaces of all finished plates which were rolled by combination reductions at 840°C and 635°C were scaled, checked, and very rough. Plate No. 49 which was reduced 90% at 635°C was smooth and uniform. Autoradiographs indicated separation or segregation of the core material in all plates, and this condition was confirmed by measurements of the cladding thickness. Metallographic examination of the bond between the Zr alloy cladding and the uranium core at 1000X showed a continuous diffusion layer with no evidence of defects or voids in the bond. This bond could not be separated by mechanical or destructive testing. The bond between Zr-Sn alloy cover plates and picture-frame along the edge and at the end of all plates was discontinuous or nonexistent. Vacuum annealing the alloy plate before assembling the billet did not improve the edge bond.

It may be concluded that zirconium-tin alloy can be roll bonded to uranium by the modified picture-frame process. Although the Zr-Sn alloy used for these tests could not be bonded to itself at the edges, and lack of ductility resulted in clad thickness variations and poor surface, particularly when rolled at 840°C, it is possible that an alloy with less iron and carbon contamination might overcome some of these difficulties. Rolling of billets without a steel can does not seem feasible.

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9. Development of Zrclad Uranium Plates for Heat Thru-Put Testing

The heat transfer characteristic of clad plates has been regarded with uncertainty. The possibility of cladding failures resulting from localized heating adjacent to bond defects may be a vulnerable characteristic of Zrclad uranium. Special test plates have been developed for the Argonne Large Scale Heat Loop to be available if this test is considered necessary. The important feature of these plates is the longitudinally tapered core which is expected to limit the tendency for concentration of electrical flux at the ends of the core, and permit larger power inputs, (see Figure 15a). Electrical connections to the plate are made through copper to nickel lugs flash welded onto the ends of the zirconium clad plate.

The billet consisted of an uranium core, 3.6" long by 2.0" wide by 1.0" thick at the middle third of the length and tapered toward the ends. The inside shape of the jacket was machined to conform to the taper of the core as shown in Figure 15b. The jacket was assembled onto the core by the press welding technique and inserted into the steel can. Details of the manufacturing methods are given in Table XII.

The acceptance of plates for heat thru-put testing depends upon satisfactory pre-tests in corrosion and dimensional stability in moderate thermal cycling. Four plates have been corrosion tested for 128 hours at 250°C without failure. Thermal cycling results for typical clad plates are given herein under cycling, and it is indicated that the effect of a few cycles (say 10 or 20) in the course of heat thru-put tests will have very little effect on plate dimensions whether beta heat treated or not.

VI. HEAT TREATMENT OF CLAD PLATES

Beta heat treatment of long thin plates was taken under consideration. Prevention of warping during heat treatment was the chief problem. The objective of this work was to develop a method for treating test specimens.

Two methods of heating for quenching were tested. The first method, heating in an induction heated graphite sleeve, developed extreme variations in plate temperature when practical heating rates were used. Consequently, this method was discarded. The second method, direct coupling in an induction coil of special design, appeared promising. Plates up 2-1/2" in width were heated uniformly to the quenching temperature in 15 to 20 seconds.

An investigation of quenching methods was undertaken to determine whether a slower rate of quenching would result in less distorted plates which would still retain reasonably good dimensional stability on subsequent thermal cycling. Zrclad uranium plates were quenched in water, between water cooled copper chill plates, in oil, and in air. The grain size was determined metallographically, and dimensional stability was determined on samples cycled in NaK 250 times between 100°C and 550°C with a 10 minute heating time and a 20 minute cooling time.

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The uranium cores in plates which were quenched between chill plates were of approximately the same grain size as in water quenched plates. Oil and air quenched plates were much coarser in grain size. The dimensional stability in terms of K factor* and degree of surface distortion for the several tests were as follows:

Treatment		K factor	Surface Condition
a. Water quench	Length	12	Slight warp
	Width	6	No bumping
b. Chill plate quench	Length	6	Slight warp
	Width	6	Slight bumping
c. Oil quench	Length	15	Slight warp
	Width	0	Severe bumping
d. Air quench (fan)	Length	10	Slight warp
	Width	8	Severe bumping

The principle difference in performance of these plates during cycling is in the degree of bumping. It appears that chill plate quenching of fuel plates would produce a structure suitable for specimens for such tests as corrosion and heat thru-put testing.

VII. TESTING METHODS AND RESULTS

The evaluation of the effects of cladding variables was based upon corrosion tests, metallography, autoradiography, thermal cycling, and physical testing of the bond. The testing methods and results are of interest and will serve to assist the reader in appraising the product quality. Compilation of reactor design data was not within the scope of these tests.

1. Corrosion Testing

An autoclave corrosion test is an excellent method for locating discontinuities in the cladding on uranium plates. The cladding itself is quite resistant to corrosion by high temperature water while the uranium corrodes rapidly. Defects in the cladding allow reaction between the uranium core and the hot autoclave water, resulting in rapid and very obvious damage to the plate. These tests were not intended to evaluate the corrosion resistance of the zirconium cladding, but to establish the integrity of cladding edge seals and end seals. In this investigation twenty one (21) sample plates, representing significant processing variables, were tested:

$$*K = \frac{1}{N} \ln \frac{L}{L_0} \cdot 10^6$$

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- a. Various cladding thicknesses from 0.005" to 0.025".
- b. Cylindrical billet, box type billet, and press welded billet, assembly methods.
- c. End seals made by welding and by preassembly welding of the ends in the billet.
- d. Edge seals made by roll-bonding of zirconium to zirconium by prewelding, and by post-rolling welding.

The test consisted of exposure in static water at the temperatures and for times indicated in Table XIII. No attempt was made to control water purity. It will be noted that survival of exposure to 250°C water was not unusual. Of the twenty-one (21) plates tested only six (6) failed.

It is noted that the most frequent point of corrosion failure was related to the welding closures made subsequent to rolling. Plate No. 6 is an exception to this statement; this plate was not welded either before rolling (in the billet stage) nor afterward, but depended upon roll bonding between zirconium and zirconium to establish a seal at the edge. All joints or closures made by welding the billet and subsequent rolling, withstood at least as much corrosion exposure as the welded end seals on the same plates. The occurrence of white corrosion product on pre-rolling welds indicates that improved gas shielding of welds would be desirable.

In Figure 16 is shown the failure which occurred in plate No. 6 rolled from an evacuated billet assembled without prewelding (see Tables III and XIII). Figure 17 shows three plates which survived testing. Figure 18 shows a plate made by the press welding technique without evacuation which was trimmed after rolling and rewelded at the edges (see Table XIII, sample 5 welded).

It is significant that of the various types of end seals tested, all gave indication of being suitable for further development. The welded seals made over exposed core metal proved least reliable, but considering the fact that little effort was made to develop skill in the technique - most welds were made free-hand - the results should not be discouraging. Welded end seals would have the advantage that long strips of clad plate could be cut to specific lengths with reasonable tolerances. If accurate plate lengths are required and further effort to develop welded seals fails, the zirconium extension of the core at the plate end - cited in Table XIII, 26b, 27b, and 43a and 43b is also a promising procedure. In any case, evaluation of end seals, and also edge seals, will have to be verified by demonstration of uniform corrosion resistance of a large number of test plates.

2. Metallography

Microstructures developed at the interfaces of Zrclad uranium are extremely thin, and difficult to interpret. Metallographic examination is valuable in establishing the uniformity of cladding, and the frequency of

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inclusions or voids in the bond. Figure 19 shows a layer between zirconium and uranium which is interpreted to be a product of interdiffusion with a phase existing between zirconium and the original interface on one side, and between uranium and the original interface on the other. The tiny black stringers are taken to be inclusions in the interface. Discontinuities at the bond interface could be clearly defined from metallographic specimens as shown in Figure 20. Judgment of bonding in this investigation depended upon the occurrence of the diffusion layer and lack of voids or inclusions in the interface indicating good contact between the dissimilar metals.

Early in the development of the cladding method, considerable reliance was put on metallographic interpretation. However, experience indicated that slight variations in metallographic procedure were significant, and in some cases plates which proved satisfactory in mechanical tests were underestimated metallographically.

Metallographic measurements of cladding thickness were made on a large number of sections from a variety of plates. Plates were prepared by cutting sections at six (6) regularly spaced intervals along the plate. These sections were ground to 600 grit on wet metallographic grinding paper and heat tinted. The measurements were made with a monocular microscope with an eyepiece calibrated to read 0.0002". These measurements were studied to determine the occurrence of localized and general variations in cladding thickness. Some of the results of these measurements were referred to in earlier sections of this paper and the results are included in Tables V, VI, VII, VIII, X, and XI. Figure 21 shows a macro-section of a 5" wide plate. The sections were taken at 7" intervals along the length of the plate and illustrate typical width and cladding thickness uniformity.

3. Autoradiography

A majority of the clad plates produced in this investigation were subjected to an autoradiograph examination. Radiation emanating from the normal uranium core resulted in exposures on X-ray film resembling normal X-ray exposures. These autoradiographs proved an effective means of locating the core material relative to the edges and ends of rolled plates and also in revealing defects in the cladding, core separation or segregation, and variations in the cladding thickness.

Clad plates were placed with one side in contact with Kodak Type K Industrial X-ray film. Portions of the film extending beyond the plate edges and ends were exposed with a flashlight to furnish an accurate outline of the entire plate. An exposure time of 16 to 20 hours gave a gradient contrast to the film through 5 to 20 mils of zirconium cladding.

Figures 22a through 22f show representative autoradiograph sections which illustrate typical conditions noted in various clad plates.

Figure 22a taken from plate No. 75 which was rolled by a combination of gamma and alpha rolling, shows an irregular core end. Uranium from the

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core was partially extruded between the zirconium cover plate and the zirconium end plug in the billet during rolling. This irregularity was most often noted in plates which had been rolled at 840°C.

The core in Figure 22b shows very irregular deformation of the core metal during rolling. This autoradiograph is from plate No. 72 which was rolled at 840°C and 635°C with a previously beta treated core. As might be expected from the appearance of the autoradiograph, cladding variations in this plate were extreme.

Although the core in Figure 22c is quite uniform, there is a distinct periodic variation or rippled effect which was noted in several plates and may be related to rolling procedure. This was a section from plate No. 80 which was rolled to 90% reduction at 635°C. Measurements indicated that the cladding thickness on this plate was quite uniform.

Figure 22d shows a section of plate No. 50 which was clad with zirconium-tin alloy and rolled at 840°C and 635°C. This figure clearly shows segregation of the core material and defects in the edge bond. Segregation of the core resulted in severe variations in the clad thickness.

A section from plate No. 87, as shown in Figure 22e, shows a lap in the zirconium cladding which developed in the middle of the plate. Plate 87 was reduced 90% at 640°C with a double beta treated core. The zirconium lap probably resulted from severe bending or distortion of the billet during rolling.

An example of uniform core distribution, cladding thickness, and core end, is shown in Figure 22f. This autoradiograph was taken from plate No. 84 which was reduced 90% at 640°C with a triple beta treated core. Measurements indicated that the thickness of cladding on this plate was exceptionally uniform.

4. Thermal Cycling

The objectives of thermal cycling in connection with this program were: (a) To determine if the effect of thermal cycling upon clad plates would be a critical consideration in designing plates for testing in the Argonne Large Scale Heat-Thru-Put Loop; and (b) To determine the effect of the growth tendency of the uranium core on the cladding and bond.

Table XIV gives the actual and percent growth of specimens approximately 2" square, cycled 250 times between 100°C and 550°C with a 10-minute heating time and 20-minute cooling time. The heating and cooling medium was NaK. Those plates which were beta treated were heated in lead at 725°C with a two minute heating and holding time, followed by quenching in water at room temperature. Transfer from the lead to water was accomplished in one second. The annealed samples were heated for two hours at 575°C and air cooled. Condition of the plates after cycling is shown in Figure 23.

The data in Table XIV show that beta treatment reduced the amount of dimensional change with respect to an alpha rolled sample and indicates that cladding has some restraining effects on beta treated plates.

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No visible defects were found in the cladding on any of these specimens after cycling. The survival of the bond under these conditions is taken as evidence of its strength. The small amount of growth resulting in this series of tests seems to indicate that heat thru-put testing of clad plates without beta heat treatment would be possible. For extended testing in which the loop might be heated and cooled several hundred times over a range of temperatures from 20°C to 250°C or more, beta treatment of the plates would be advisable.

5. Mechanical Testing

A tensile test normal to the plane of bonding was devised, and a considerable amount of time was spent in an attempt to develop the test to a reliable routine method, but success was limited. The specimen was made by percussion welding the end of a 1/4" diameter zirconium rod or stud to the cladding on opposite sides of the plate. The assembly was then machined to a miniature tensile specimen as shown in Figure 24. Subsequently, the zirconium adhering to the stud was pulled from the core in a tensile testing machine. The welding technique was found to be extremely critical. Slight variations in power produced variations in weld quality ranging from incomplete welding to overheating of the zirconium-uranium bond. The reliability of each test had to be checked metallographically to determine if the bond had been affected by welding heat. The microstructure of a weld in which the cladding and core metal were affected by welding is shown in Figure 25a. The microstructure of a satisfactory weld is shown in Figure 25b. Combined metallographic examination and tensile testing of the bond did establish that bond strengths in the range of 50,000 psi were possible by combination gamma and alpha rolling. It was established through the tensile test that a 55% reduction by rolling of the billet in the gamma temperature range produces a 10,000 to 15,000 psi bond strength. A 30% gamma reduction followed by alpha reduction to a total of 75% develops essentially no bond.

In addition to results obtained from direct tensile testing of clad plates, data were obtained on bond quality as well as plate formability from bend tests. Representative 1/2" wide test strips taken at 90° to the direction of rolling from 1/8" thick clad plates, were subjected to a guided bend test around mandrels with 1/8" and 1/16" radii. Measurement of the angle through which strips could be bent before rupturing furnished a quantitative evaluation of plate formability resulting from different methods of cladding. The adherence of the cladding to the core at the point of rupture gave a qualitative or relative measure of bond strength. Table XV summarizes the bend test results.

From the results of bend tests on specimens from a number of plates, several conclusions may be made regarding the effect of material and rolling variables on plate ductility. The usual differences in the initial hardness of arc melted crystal bar zirconium was believed to have little or no effect on the ductility of rolled plate. Plates clad with Bureau of Mines Zr-3% Sn alloy

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and arc melted sponge zirconium were not as ductile as those clad with Grade III crystal bar zirconium. The relation of core material to ductility could not be determined as there was little variation in core material in these tests. One group of tests on core material alone, from which the zirconium cladding had been removed, indicated a surprisingly high ductility for alpha rolled uranium plate. Billets rolled in a combination of gamma and alpha temperature ranges appear to have the same ductility as those rolled in the alpha temperature range only, provided the alpha temperature is not less than 630°C. There seems to be little doubt that outgassing from C-1020 carbon steel cans has a deleterious effect on plate ductility whereas plates rolled in Armco Iron or Ti-namel steel cans are more ductile.

6. Heat Thru-Put Testing

Heat thru-put testing of clad plates was considered as a means of determining the effect of variable heat transfer characteristics resulting from irregular bonding. A plate was developed which is thought to be suitable for testing in the Argonne Large Scale Heat Thru-Put Loop.

VIII. EQUIPMENT AND MATERIALS

1. Equipment

All of the manufacturing operations in this investigation were performed on the existing facilities in the ANL shops and laboratories. The equipment used for machining, welding, and testing were of standard type such as would be used in any industrial shop. The equipment used for billet processing was more specialized. A short description of this equipment is given in the ensuing paragraphs.

a. Rolling Mill - 16" x 24": All hot rolling of billet stock and cladding billets was accomplished on the 16" x 24" United Mill shown in Figure 26. The mill housing is of closed top design and supports power driven screws for adjustment of the top roll. A balancing mechanism (springs) is provided for the top roll. The roll neck bearings are of bronze and are mounted in steel chocks.

The mill is driven with a variable speed, direct current, shunt wound motor, 150/200 H.P., 400/1200 RPM, 230 volt. The mill is driven through a 150 H.P. double reduction, combination drive and pinion stand. The total gear reduction is 15.56 to 1.

Operation of the mill, generator, and oil pump are controlled from the single control panel shown in Figure 26. The mill may be run in either direction at speeds ranging from nearly 0 to 300 ft/min.

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Strippers are provided to guide the work as it is delivered from the rolls when using oval-edge oval rolls and open square rolls. A foreplate is mounted on the mill to aid in entering the work. For roll cladding billets a set of entry guides was mounted on the foreplate as soon as initial passes had lengthened the billet to about 12". It was found that production of straight finished plates was largely dependent upon skillful use of these guides.

Three sets of rolls were used in the 16" x 24" mill. For hot flat-rolling, 16" diameter flat rolls were used which were concentric within about 0.010", and had fairly smooth surface finish. Preliminary breakdown of uranium ingots, and also a few of the cylindrical cladding billets, was accomplished on rolls with open-square grooves as shown in Figure 27. The oval-edge oval rolls, shown in Figure 28 were used for preliminary breakdown of some of the cylindrical cladding billets.

b. Rolling Mill - Four High - 5-3/4" x 16" x 12": All finish rolling was accomplished on the Bliss 4-high mill shown in Figure 29. This mill is provided with power driven adjusting screws and individual hydraulic balancing on each end of each roll. The roll necks turn in roller bearing races. A lubricant sump is located in a pit under the mill and a pump and piping system is installed to provide a flood of lubricant to the work-roll faces.

This mill is driven by a variable speed, direct current, shunt wound stabilized motor, 50 H.P., 690/1200 RPM, 230 volts. The mill is driven through a 50 H.P. rated, reduction drive and pinion stand. Total reduction is 20:1. Operation of the mill is controlled from the panel shown in Figure 29. The mill may be run in either direction and speed controlled from 50 to 200 ft/min. Controls are provided for individual or simultaneous adjustment of the adjusting screws.

A guide roll arrangement was used for all finishing operations. The arrangement shown in Figure 29 was sufficient to produce straight finished plate when the hot rolled stock was straight to begin with.

c. Furnace Equipment: The rolling operations described herein were carried out in the range of 630°C or a combination of 630°C and 840°C temperature. A Hevi-Duty electric muffle furnace shown in Figure 30 was used for the higher temperature heating. The muffle is 18" wide, 12" high, and 72" long. The temperature limit is 975°C and the temperature is controlled by means of Leeds and Northrup Micromax Controller and recorder.

In the early part of this program the low temperature heating was accomplished in molten lead. The furnace consists of a cast high nickel alloy tank 10" wide, 14" deep, and 84" long. The tank is supported in an insulated shell which also supports the resistance heaters about the tank. Furnace rating is 70 KW at 220 volts. The lead temperature is controlled

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with a Leeds and Northrup Micromax and a separate indicating thermocouple is located in the lead. The lead furnace is shown in Figure 31. A fume hood is provided to safeguard health.

Lead heating is fast and convenient, but it was found that lead adhering to the work lubricated the billet and made entry into the rolls at desired reductions difficult. The scale produced on the steel cans in muffle furnace heating proved a more suitable surface for rolling.

d. Roll Straightener: All hot rolled plates were flattened on a roller leveler to facilitate stripping the steel can from the clad plates by shearing. A 3-1/2" x 15" Waterbury Farrel Nine Roll Straightener was used. The straightener is powered by a 15 H.P., 440 volt, 640 RPM, 3 phase Westinghouse motor with a drive ratio of 5.86 to 1. Guide rolls on the entering side of the straightener and a run-out table on the discharge side facilitate handling of heavy plates. The run-out table is an 18" wide x 16' long Rapistan Rapid-Roller Conveyor. This equipment is illustrated in Figure 32.

e. Cleaning and Surface Preparation: Electropolishing, Vaporblast, Sandblast, and Mechanical Polishing were all tried as a means for removal of surface oxidation on uranium and zirconium. No differences in the bonding as a result of the method of surface preparation was detected. Vaporblasting of zirconium and mechanical polishing of the uranium proved to be the most convenient.

Mechanical polishing was performed on a 4" x 12" Porter-Cable belt polisher provided with an exhaust hood. Finishing by hand was usually necessary in order to get uniform clean surfaces.

All zirconium surfaces were cleaned in a Vaporblast Model B-20. This machine consists of a metal cabinet with a sight glass, and glove openings for the operator. The bottom of the cabinet forms a sump in which a grit and water suspension is collected. The grit suspension is pumped through pipes to a nozzle in the operator's hand; when cleaning, a pedal operated air valve is open and compressed air piped into the nozzle vaporizes the suspension and blasts it against the work. No. 100 alundum grit was used with a special additive to prevent the grit from settling and packing.

f. Testing Equipment: Standard laboratory equipment was utilized for corrosion testing, metallography, autoradiography, and mechanical testing. Thermal cycling was accomplished in an induction heated NaK filled bomb. Heat input to the bomb is controlled by a program type instrument coupled with thermocouples in the bomb. A complete description of this equipment and its operation is given in Reference 2.

2. Materials

All of the normal uranium core material, uranium-zirconium alloy core material, and zirconium sheet used for cladding on this project were cast and fabricated into slab and sheet with available facilities at ANL. The

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Zr-3% Sn alloy and sponge zirconium were obtained from the Bureau of Mines. The Armco iron, medium carbon steel, and Ti-namel, (titanium killed steel), which were used for can materials were all of commercial grade.

Normal uranium which was received as Mallinckrodt Biscuit metal, or as scrap slugs, was induction melted in graphite crucibles. The molten uranium was cast into graphite molds at 1400°C. Cast billets of 3" x 3" x 20" were then rolled in open-square passes to 2-1/4" square at a temperature of 600°C out of a salt bath. These square billets were flat rolled to 1-1/8" thick x 5" wide slabs which were machined to the final core sizes. The combined rolling operations resulted in a maximum total reduction of 60% in thickness from the cast billet.

The U-2% Zr alloy was made from remelted uranium slugs and Westinghouse Grade III Crystal Bar zirconium. This alloy was arc melted in a water cooled copper crucible with a water cooled electrode having a 1/2" diameter tungsten tip, in an atmosphere of 20% argon - 80% helium. The arc melted 3" diameter x 12" long cast ingot was heated to 700°C in a molten lead bath and rolled in open-square passes to a 2" square billet. This square billet was flat rolled to a 1-1/8" thick x 5" wide slab and machined to the final core sizes.

Westinghouse Grade III Crystal Bar zirconium was arc melted in a water cooled copper crucible with tungsten tipped electrodes in a 20% argon - 80% helium atmosphere to produce 6" diameter x 15" long ingots. The cast ingots were forged at 850°C to 2" x 6" rectangular billets. Approximately 1/16" of metal was removed from the surface of the forged billets by scalping to remove oxide scale and surface defects. The forged billets were hot rolled from a lead bath at 700°C to a final thickness of about 1/4". Hot rolling reductions were on the order of 5-15% per pass with 4 passes per reheat. Strip was finished to required thickness for cladding by cold rolling with total reductions of 40% followed by annealing at 700°C.

Chemical and spectrographic analysis of representative materials supplied for this project may be found in Table XVI.

IX. ACKNOWLEDGEMENTS

This report represents an interpretation of data taken from plates which were planned, manufactured, and tested for this program. The volume of detail work involved was considerable, and was only accomplished by virtue of the advice and assistance of members of the Argonne Metallurgy and Reactor Engineering Divisions. The authors wish to acknowledge the contributions of the following individuals at ANL:

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2. ANL-4848, S. T. Zegler and R. M. Mayfield: Thermal Cycling Equipment.

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CODE & NOTES FOR TABLES III THROUGH XI

1. R. - Percent Reduction (total)
2. R.M.S. - Remelted slugs
3. V.B. - Vapor blasted
4. S.B. - Sand blasted
5. E.P. - Electro-polished
6. M.P. - Mechanical polished (equal to 120 grit)
7. Bonding classification: (based upon judgment guided by metallography, mechanical tests, general response to fabrication).
 - A. Satisfactory - exhibits no microdefects, withstands cold finishing, shearing, and bending. If determined, the bond tensile strength exceeds 20,000 psi.
 - B. Doubtful - no apparent defects, but can be separated by bending. Tensile strength of bond less than 20,000 psi.
 - C. Unsatisfactory - visible defects.
8. M.P.F. - Modified Picture Frame Billet
9. Box - Zirconium billet parts welded into a box before assembling billet.
10. P. W. - Billet assembled in press before zirconium jacket is welded.
11. T_A - Average Clad Thickness - determined by averaging thickness measurements taken at 0.100" intervals across both sides of 6 sections, equally spaced along the length of plate.

Dev._A - Average Deviation - determined by summing the differences (not algebraically) between average clad thickness and each measurement, and dividing by total number of measurements.

Dev._R - Range of Deviation - Greatest positive and negative deviation observed.

T_M - Minimum Clad Thickness - As observed.

V_A - Average Variation - Sum of differences between each pair of measurements (0.100" apart), divided by number of individual variations determined.

90% Meas. - 90% of Measurements Range - The frequency of occurrence of various clad thicknesses observed was plotted. The narrowest range of thickness embracing 90% of the measurements was recorded.
12. Tsi - Tons per square inch.
13. O-E-O - Oval-Edge-Oval.

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Table I

HOT ROLL BONDING SCHEDULE: ZRCLAD URANIUM

Pass No.	Temp. °C	Reduction (in)	Gage	Micrometer Gage (in)	Remarks
1	800 ⁽¹⁾	0.050	0.575	--	Cool to 630°C
2	630 ⁽²⁾	0.100	0.475	0.492	Reheat for 5 minutes
3	630	0.085	0.390	0.410	Reheat for 5 minutes
4	630	0.085	0.305	0.327	Reheat for 5 minutes
5	630	0.085	0.220	0.247	Reheat for 5 minutes
6	630	0.050	0.170	0.194	Reheat for 5 minutes
7	630	0.040	0.156	0.156	- - -

(1) Heat to 800°C in muffle furnace for first pass.

(2) Cool to 630°C in muffle furnace for subsequent passes.

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Table II

EFFECT OF INTERNAL BILLET ATMOSPHERE ON BONDING OF ZIRCONIUM TO URANIUM

Billet No.	Can Material	Notes on Internal Billet Atmosphere	Accumulated Billet Interface Spacing on each Axis	Zr-U Surface Condition After Disassembly
1	C-1020 Steel	Evacuated.* 20 min. to 500 microns. 24 hours to 35 microns. Heated to 845°C - 1 hour.	0.008"	U: almost covered with fluffy black scale. Zr: almost covered with black and white scale.
3	C-1020 Steel	Evacuated. 30 min. to 5 microns. 14 hours to 1 micron. Max. pressure during heating 200 microns. Total heating time at 845°C - 72 hours.	0.030"	U: both were metallic bright. Zr:
13	C-1020 Steel Vacuum Annealed	Evacuated. 5 min. to 50 microns. Max. pressure during heating 200 microns. Heating from 400°C to 850°C in 3 hours.	0.010"	U: slightly scaled at center. Zr: unaffected.
2	C-1020 Steel	Not evacuated. Zr jacket sealed by heliarc welding before assembly into steel can. Heated to 800°C, 1 hour.	0.008"	U: uniformly covered with a very thin gray powder-like deposit. Zr: unaffected.
5	C-1020 Steel	Not evacuated. Zr jacket sealed by heliarc welding before assembly into steel can. Heated to 840°C.	0.008"	Rolling with 10:1 reduction produced bonding of indicated tensile strength of the order >20,000 psi.
6	C-1020 Steel Vacuum Annealed	Evacuated. Billet sealed at 10 microns. Heated to 840°C.	0.008"	Rolled with 10:1 reduction. Metallographic examination of the plate indicated bonding equal to 5. Corrosion tests in 170°C water produced corrosion failures which appeared to originate in the Zr-Zr interface at the edges of the plate.

*Evacuated billets were connected to a vacuum system at 10^{-5} mm pressure. After the lengths of time noted, the recorded pressures were observed with a thermocouple gauge installed in the end of the billet furthest from the pumping system.

Table III

DATA FROM EXPLORATORY ROLLING OF FLAT BILLETS

Billet No.	Billet Design	Origin of Uranium	History of Core Material	Preparation		Cladding Billet Reduction/Pass	Total Reduction (Accumul.)	Rolling Temp.	Passes Per Reheat	Bonding ⁷ Eval.	Cladding Surface & Dimensions	Significant Variable	Remarks	Results
				Clad	Core									
4	M.P.F. ⁸ Box ⁹	4D663	60% R ¹ -RMS ²	V.B. ³	E.P. ⁵	1.5% 5.0 to 15%	6% 93%	840°C 635°C	1 3	B	B	0.004" interface tol. Air not evacuated from billet.	Bonding but not strong	
5	M.P.F. Box	4D663	60% R-RMS	V.B.	E.P.	1.5% 5.0 to 15%	6% 93%	840°C 635°C	1 3	B	B	0.002" interface tol. Not evacuated.	Close tolerance required special machining.	Bond appeared somewhat stronger than 4.
6	M.P.F. Loose Assembly	4D663	60% R-RMS	V.B.	E.P.	1.5% 5.0 to 15%	6% 93%	840°C 635°C	1 3	C (Zr Bond)	B	0.002" interface, can material was vacuum annealed C-1020 steel evacuated to 10 microns at 840°C.	Evacuation requires too long. C-1020 vac. annealed shows no tendency to appreciable outgassing.	Zr-U bond satisfactory. Zr-Zr bond not corrosion resistant.
7	M.P.F. Box	4D663	60% R-RMS	V.B.	E.P.	1.5%	6%	840°C	1			0.005" interface.	Stainless steel cans failed at these low rolling temperatures.	Tests showed some bonding in each case.
8						7. 5.0 to 15%	81%	635°C	3	B	B	Cans were Type 347		
9						8. 5.0 to 15%	85%	635°C	3	B	B	stainless steel.		
						9. 5.0 to 9%	90%	635°C	3	C	B			
14	M.P.F. Box	4D663	60% R-RMS	V.B.	E.P.	1.5% 11.0 to 15%	6% 78%	840°C 635°C	1 3			0.004" interface. Intermediate gamma roll to enhance bonding.		Intermediate gamma rolling developed coarser finish grain size.
						10.0%	84%	840°C	1					
						15.0%	90%	635°C	3	A	B			
20	M.P.F. P.W. ¹⁰	4D692	60% R-RMS	V.B.	M.P. ⁶	1.5% 11.0 to 15%	6% 78%	840°C 635°C	1 3			0.002" interface Jacket assembled on core with pressure of 2 Tsi. ¹² Welded between chill plates.	Reduced time for assembly. Welds improved.	Plate of good quality, but intermediate gamma rolling probably coarsened uranium.
						10.0%	84%	840°C	1					
						15.0%	90%	635°C	3	A	B			
25	M.P.F. P.W.	4D660	60% R-RMS	V.B.	M.P.	2.5 to 11% 15.0%	21% 95%	840°C 635°C	1 3	A	B+	Rolled for 0.005" thick clad.	0.150" - 0.200" drafts between 1.0" and 1.5" gage stalled mill.	Plate was of good quality except for camber.
26	M.P.F. Box	4D660	60% R-RMS	V.B.	M.P.	2.5 to 11% 10.0%	21% 90%	840°C 635°C	1 3		B+	Rolled for 0.025" thick clad.	For corrosion tests.	Plate satisfactory.
27	M.P.F. P.W.	4D692	60% R-RMS	V.B.	M.P.	2.5 to 11% 10.0%	21% 90%	840°C 635°C	1 3		B+	Billet altered to provide long (5") Zr section at end.	Long Zr end to provide end seal. See corrosion testing.	Plate satisfactory.
28	M.P.F. P.W.	4D692	60% R-RMS	V.B.	M.P.	2.5 to 11% 10.0%	21% 90%	840°C 635°C	1 3		B+	Rolled for 0.005" thick cladding.	See corrosion testing.	Plate satisfactory.
43	M.P.F. P.W.		60% R-RMS	V.B.	M.P.	5.0 to 10% 10.0%	45% 90%	840°C 635°C	2 2		B	Ti-namel can. Rolled for 0.010" clad for corrosion test.	Ti-namel partially bonded to Zr. See corrosion testing.	Plate satisfactory.

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Table IV

DATA FROM EXPLORATORY ROLLING OF CYLINDRICAL BILLETS

Billet No.	Billet Design	Origin of Uranium	History of Core Material	Preparation		Cladding Billet Reduction/Pass	Total Reduction (Accumul.)	Rolling Temp.	Passes Per Reheat	Bonding Eval.	Cladding Surface & Dimensions	Significant Variable	Remarks	Results
				Clad	Core									
10	Cylinder Flat Rolls	Special	As cast into Zr jacket	---	---	2.5% 14 to 10%	10% 90%	840°C 635°C	1 3	A	B	Cast-in jacket technique. Object, to save machining cost.	Billet rolled satisfactorily. Rolled plate had a cigar shape section.	Bond established in casting operation. As rolled bond was excellent, & was uniform over 95% or more of interface.
11	Cylinder Flat Rolls	5D744	Machined from cast ingot	V.B.	M.P.	2% 10 to 20%	6% 95%	840°C 635°C	1 3	B	B+	Flat rolling of fabricated cylinder billet.	Rolling satisfactory. Surfaces slightly undulated. Edges not parallel. Section cigar shaped.	About 80% of interface bonded - no edge bond - cladding distribution was acceptable.
37	Cylinder Open-square & Flat Rolls	---	Machined from cast ingot	V.B.	M.P.	Open-squares 4 to 8% Flat 4 to 10%	73% (1-1/2" x 1-1/2") 97%	840°C 635°C	2 2	A	C	Rolling in open-square passes to initiate bonding at edge.	Rolling manipulation considerably easier than O-E-O. Finish with perfect square requires extra care.	Cladding in square section very irregular, persisted in flat rolling. Bonding good.
38	Cylinder Open-square & Flat Rolls	---	Machined from cast ingot	V.B.	M.P.	Open-squares 4 to 8% Flat 4 to 10%	52% (2" x 2") 97%	840°C 635°C	2 2	A	C	Rolling in open-squares to initiate bonding. Smaller reduction in squares to obtain more uniform cladding.	Can showed no evidence of pinching. Sections showed core to be pinched and jacket was irregular in thickness.	Cladding was irregular in thickness. Bonding good.
12	Cylinder O-E-O ¹³ & Flat Rolls	5D744	Machined from cast ingot	V.B.	M.P.	O-E-O 1 to 3% 4% Flat 9% 15%	10% 30% 25% 90%	840°C 635°C 840°C 635°C	1 1 1 4	B	B	Preliminary rolling in O-E-O passes to work entire circumference, intend to initiate bonding all around interface.	Light reduction in oval passes, but some pinching in rolls.	About 80% of interface bonded no edge bond - cladding distribution irregular.
22	Cylinder O-E-O & Flat Rolls	5D754	Machined from cast ingot	V.B.	M.P.	O-E-O 1 to 4% Flat 5 to 8% 10%	33% 80%	840°C 840°C 635°C	1 2 3	See Remarks		Flat rolled in 4 hi-mill at 635°C.	Plate became so badly rippled and bent during 4-hi mill reductions that rolling could not continue.	None.
31	Cylinder O-E-O & Flat Rolls	---	Machined from cast ingot	V.B.	M.P.	O-E-O 1 to 4% Flat 5 to 13%	33%	840°C 635°C	1 3	B	C	Rolling in oval passes, major and minor axis of section interchanged on last pass to obtain max. preliminary working of edges.	The oval passes pinched the billet.	Cladding distribution was very irregular.
40	Cylinder O-E-O & Flat Rolls	---	Machined from cast ingot	V.B.	M.P.	O-E-O 5 to 10% Flat 5 to 10%	41% 91%	840°C 635°C	2 2	A	C	Major & minor axis of section were interchanged on last pass. Used heavy reductions to determine if less overfilling would result.	Overfilling was increased.	Plate dimensions and surface were unsatisfactory. Bonding was good.
39	Cylinder O-E-O & Flat Rolls	---	Machined from cast ingot	V.B.	M.P.	O-E-O 2 to 4% Flat 5 to 10%	43% 96%	840°C 635°C	2 2	See Remarks		Canned in Type 347 stainless instead of usual C-1020 or Armco-iron.	Can broke in rolling. Stainless apparently not suitable for rolling at the temperatures of interest.	Not satisfactory.

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Table V

EFFECT OF URANIUM GRAIN SIZE AND ROLLING TEMPERATURE ON CLADDING THICKNESS UNIFORMITY

Billet No.	Billet Type & Tolerance	Origin of Uranium	History of Core Material	Preparation		Cladding Billet Reduction/Pass	Total Reduction (Accumul.)	Rolling Temp.	Passes Per Reheat	Bonding Eval.	Cladding Surface & Dimensions	Cladding Dimensions ¹¹ - mils						Significant Variable	Remarks	Results
				Core	Clad							T _A	Dev. A	Dev. R	T _M	V _A	90% Meas.			
65	M.P.F. -P.W. .003 in/in ²	803	As-cast; R.M.S.	M.P.	V.B.	5 to 7% 7 to 10%	30% 90%	840°C 635°C	2 2	A	C	12.5	1.26	+3.6/ -4.9	7.6	1.18	9.5 to 15.0	As-cast core; unrefined cast structure.	Max. clad. variation if orientation and grain size are significant.	Clad variation was average.
66	M.P.F. -P.W. .003 in/in ²	4D683	60% R.; R.M.S.	M.P.	V.B.	5 to 6% 6 to 7% 7 to 10%	15% 30% 90%	840°C 840°C 635°C	2 1 2	A	B	12.7	1.84	+4.6/ -3.7	9.0	0.89	10.0 to 16.0	60% R. core. partially refined.	Partial refinement expected to improve clad uniformity.	Clad variation poorer than average.
72	M.P.F. -P.W. .003 in/in ²	4D683	60% R.; R.M.S. β treated	M.P.	V.B.	5 to 7% 7 to 10%	25% 90%	840°C 635°C	2 2	A	C	13.4	1.7	+6.1/ -5.1	8.3	1.48	10.4 to 17.0	60% R. core; β treatment increased refinement of core.	Core refinement expected to improve clad uniformity.	Clad variation extreme.
73	M.P.F. -P.W. .003 in/in ²	4D697	60% R.; R.M.S. β treated	M.P.	V.B.	5% 5%	30% 90%	840°C 635°C	2 2	A	B	13.2	1.3	+4.8/ -5.1	8.0	1.17	10.0 to 16.5	Beta treatment core for refinement; smaller reductions.	5% reduct./pass expected to reduce distortion in rolling, give uniform cladding.	Improvement not significant.
80	M.P.F. -P.W. .003 in/in ²	4D684	60% R.; R.M.S. β treated	M.P.	V.B.	5 to 10%	90%	635°C	2	A	B	12.7	1.04	+3.7/ -4.2	8.5	0.94	10.2 to 15.2	Beta treatment for core refinement; rolled in alpha to avoid grain growth.	Low rolling temp. to preserve fine grain size; improve clad uniformity.	Clad variation best for entire series.

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Table VI

EFFECT OF BETA-HEAT TREATMENT OF BILLET CORES ON CLADDING THICKNESS

Billet No.	Billet Type & Tolerance	Origin of Uranium	History of Core Material	Preparation		Cladding Billet Reduction/Pass	Total Reduction (Accumul.)	Rolling Temp.	Passes Per Reheat	Bonding Eval.	Cladding Surface & Dimensions	Cladding Dimensions - mils						Significant Variable	Remarks	Results
				Core	Clad							T _A	Dev. A	Dev. R	T _M	V _A	90% Meas.			
82	M.P.F.-P.W. .003 x .003 x .004	5D804	60% R.; R.M.S.	S.B.	V.B.	5 to 10%	90%	660°C	2	A	B	15.5	1.21	+7.7/ -2.3	13.2	0.60	13.7 to 17.7	Triple beta treated core. Plate rolled at 660°C.	Plate surface rippled with corresponding variations in clad thickness.	Cladding well bonded to core but rolling temp. too close to beta temp. range with subsequent core irregularities.
83	M.P.F.-P.W. .003 x .003 x .004	4D715	60% R.; R.M.S.	S.B.	V.B.	5 to 10%	90%	615°C	2	A	A	16.4	1.86	+2.7/ -4.8	11.6	0.76	13.0 to 17.7	Triple beta treated core. Plate rolled at 615°C.	Excellent surfaces, uniform core, no segregation uniform plate dimensions.	Plate well bonded but considerable variation in clad thickness.
84	M.P.F.-P.W. .003 x .003 x .004	4D679	60% R.; R.M.S.	S.B.	V.B.	5 to 10%	90%	640°C	2	A	B+	15.3	0.96	+3.1/ -2.9	12.3	0.62	13.0 to 17.0	Triple beta treated core. Plate rolled at 640°C.	Plate surface slightly rippled with corresponding segregation of core. Uniform plate dimensions.	Plate well bonded with quite regular clad thickness. Decided improvement in clad uniformity due to beta treatment.
85	M.P.F.-P.W. .003 x .003 x .004	5D801	60% R.; R.M.S.	S.B.	V.B.	5 to 10%	90%	640°C	1	A	B	15.8	1.50	+10.2/ -4.7	11.1	0.64	12.7 to 19.2	Triple beta treated core. Plate rolled at 640°C; reheated every pass.	Segregation of core matl. throughout plate, particularly severe at plate ends.	Cladding variations correspond to uneven movement of core matl. during rolling.
86	M.P.F.-P.W. .003 x .003 x .004	5D801	60% R.; R.M.S.	S.B.	V.B.	7-1/2 to 17-1/2%	90%	640°C	2	C	C	(See Remarks)						Triple beta treated core. Reduc. 7-1/2 to 17-1/2% per pass	Original welds on zirconium jacket cracked open early on rolling with subsequent lack of bonding over 50% of surface.	
87	M.P.F.-P.W. .003 x .003 x .004	4D707	60% R.; R.M.S.	S.B.	V.B.	5 to 10%	90%	640°C	2	A	A	16.3	1.25	+4.3/ -4.1	12.2	0.55	13.7 to 18.7	Double beta treated core. Plate rolled at 640°C.	Defects in cladding noted at plate ends and center affecting core distribution.	Cladding fairly uniform but not quite as good as with triple beta treated cores.
88	M.P.F.-P.W. .003 x .003 x .004	4D697	60% R.; R.M.S.	S.B.	V.B.	5 to 10%	90%	640°C	2	A	A	16.3	1.37	+4.1/ -3.5	12.8	0.53	13.7 to 19.7	Single beta treated core. Plate rolled at 640°C.	Light, uniform segregation of core noted on autoradiograph.	Cladding not quite as uniform as with double or triple beta treated cores.
89	M.P.F.-P.W. .003 x .003 x .004	5D880	60% R.; R.M.S.	S.B.	V.B.	5 to 10%	90%	630°C	2	B	A	16.4	1.11	+4.4/ -3.4	13.0	0.50	13.7 to 18.2	Triple beta treated core. Bu. of Mines sponge clad. Plate rolled at 630°C.	Plate surface very smooth with no segregation of core material.	Cladding very uniform but bond not as adherent as with crystal bar zirconium.
90	M.P.F.-P.W. .003 x .003 x .004	5D880	60% R.; R.M.S.	S.B.	V.B.	5 to 10%	90%	620°C	2	C	A	17.0	0.97	+4.0/ -4.3	12.7	0.47	15.2 to 18.7	Triple beta treated core. Bu. of Mines sponge clad. Plate rolled at 620°C.	Same as 89 above.	Cladding very uniform but bond discontinuous and cladding could be easily removed.

Table VII

EFFECT OF ROLLING TEMPERATURE, REDUCTION, AND FREQUENCY
OF REHEATING ON CLADDING THICKNESS UNIFORMITY

Billet No.	Billet Type & Tolerance	Origin of Uranium	History of Core Material	Preparation		Cladding Billet Reduction/Pass	Total Reduction (Accumul.)	Rolling Temp.	Passes Per Reheat	Bonding Eval.	Cladding Surface & Dimensions	Cladding Dimensions - mils						Significant Variable	Remarks	Results
				Core	Clad							T _A	Dev-A	Dev-R	T _M	V _A	90% Meas.			
81	M.P.F. -P.W. .003 in/in ²	4D684	60% R.; R.M.S. β treated	M.P.	V.B.	5 to 7% 7 to 10%	25% 90%	840°C 635°C	1 2	A	B	13.7	1.92	+ 6.3/ - 5.7	8.0	1.03	9.7 to 17.7	Combination alpha-gamma rolling temperature.	Beta treatment of core in comb. temp. rolling has no beneficial effect.	Clad uniformity poor.
77	M.P.F. -P.W. .003 in/in ²	4D682	60% R.; R.M.S.	V.B.	V.B.	5 to 10%	90%	635°C	1	A	B	12.6	1.73	+ 4.6/ - 4.0	8.6	0.60	9.25 to 16.5	Alpha rolling temp. with 5 to 10% reductions; reheating every pass.		Clad uniformity average for these tests. Zr drifts to opposite ends of plate on opposite sides.
78	M.P.F. -P.W. .003 in/in ²	5D766	60% R.; R.M.S.	M.P.	V.B.	5 to 10%	90%	635°C	2	A	B	12.9	1.24	+ 3.6/ - 7.2	5.7	1.01	9.5 to 15.5	Alpha rolling temp. with 5 to 10% reductions; reheating each second pass.	Ref. to 77. Reheats every pass maintain uniform rolling temp.	Uniformity better than 77.
79	M.P.F. -P.W. .003 in/in ²	4D684	60% R.; R.M.S.	M.P.	V.B.	5%	90%	635°C	2	A	B	13.0	1.23	+ 4.0/ - 6.1	6.9	1.28	9.5 to 15.5	Alpha rolling temp. with 5% reductions; reheating each second pass.	Limiting all reductions to 5% per pass shows no improvement over reductions of 10% per pass.	Similar to 78 above.

Table VIII

EFFECT OF RESIDUAL CARBON CONTENT ON CLADDING THICKNESS UNIFORMITY

Billet No.	Billet Type & Tolerance	Origin of Uranium	History of Core Material	Preparation		Cladding Billet Reduction/Pass	Total Reduction (Accumul.)	Rolling Temp.	Passes Per Reheat	Bonding Eval.	Cladding Surface & Dimensions	Cladding Dimensions - mils						Significant Variable	Remarks	Results
				Core	Clad							T _A	Dev-A	Dev-R	T _M	V _A	90% Meas.			
68	M.P.F. -P.W. .003 in/in ²	804MB	60% R. -MB	M.P.	V.B.	5 to 7% 7 to 10%	25% 90%	840°C 635°C	2 2	A	C	13.9	1.7	+18.4/ - 7.3	6.6	1.7	9.0 to 16.0	Core purity presumed to be good.	Min. intergranular variation of core hardness may result in less clad variation..	Clad variation extreme.
69	M.P.F. -P.W. .003 in/in ²	804MB	60% R. -MB	M.P.	V.B.	5 to 7% 7 to 10%	25% 90%	840°C 635°C	1 2	A	B	13.2	1.3	+ 5.0/ -13.1	0.10	1.12	8.0 to 16.5	Duplicate of 68.	Duplicate of 68.	Variation is less than 68. Indicates effect of some variable not under control.
70	M.P.F. -P.W. .003 in/in ²	4D631	60% R.; R.M.S.	M.P.	V.B.	5 to 7% 7 to 10%	30% 90%	840°C 635°C	2 2	A	C	12.7	1.13	+ 4.4/ - 5.1	7.6	1.02	11.1 to 15.0	R.M.S. core analysis normal carbon.	To observe effect of possible variable hardness of core.	Clad uniformity is better than obtained with either MB core.
75	M.P.F. -P.W. .003 in/in ²	4D682	60% R.; R.M.S.	E.P.	V.B.	5% 5%	25% 90%	840°C 635°C	2 2	A	C	12.7	1.84	+ 4.2/ - 3.7	9.0	1.01	10.5 to 14.9	Duplicates 70, except smaller reductions/pass.	Duplicate of 70.	Clad uniformity of same order as other plates in this group.
74	M.P.F. -P.W. .003 in/in ²	4D697	60% R.; R.M.S.	E.P.	V.B.	5 to 7% 7 to 10%	25% 90%	840°C 635°C	1 2	A	B	13.7	1.76	+16.3/ - 4.7	9.0	0.90	10.0 to 17.5	Duplicates 70.	Duplicate of 70.	Clad uniformity poor.

Table IX

EFFECT OF FINISHING METHODS ON CLADDING THICKNESS
(Plate 81 Hot Rolled in Gamma and Alpha
Temperature Ranges - See Table VII)

	Average Clad Thickness	Average Percent Deviation
As hot rolled 90%	13.7 mils	14
Cold rolled additional 8%	12.3	10.3
Oil rolled 300°C additional 54%	6.8	10.2
Lead rolled 600°C additional 61%	5.1	10.0

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Table X

DATA FROM EXPLORATORY ROLL CLADDING OF ARC MELTED U-2 w/o Zr ALLOY WITH ZIRCONIUM

Billet No.	Billet Design	Origin of Uranium	History of Core Material	Preparation		Cladding Billet Reduction/Pass	Total Reduction (Accumul.)	Rolling Temp.	Passes Per Reheat	Bonding Eval.	Cladding Surface & Dimensions	Significant Variable	Remarks	Results
				Clad	Core									
23	M.P.F. P.W.	A.M.	60% R. at 635°C R.M.S. & Grade III Crystal Bar	V.B.	M.P.	5 to 14%	91.5%	700°C	2	C	B-	Zr-U alloy core rolled in 2 phase temperature range.	Rolled satisfactory. Clad surface was pimpled.	No bond.
24	M.P.F. P.W.	A.M.	60% R. at 635°C R.M.S. & Grade III Crystal Bar	V.B.	M.P.	5 to 14%	75%	815°C	2	See Remarks		Zr-U alloy core rolled in gamma temperature range.	Core extruded out of can at 75% reduction. Rolling was discontinued.	None
42	M.P.F. P.W.	A.M.	60% R. at 635°C R.M.S. & Grade III Crystal Bar	V.B.	M.P.	5 to 10% 10%	45% 90%	840°C 635°C	2 2	A	B	Zr-U alloy cores rolled partially in gamma and partially in alpha.	Surface contour indicated alloy was harder than normal uranium at 635°C.	Good bond surface, satisfactory after cold finishing; ends broke off in cold finishing.

Table XI

DATA FROM EXPLORATORY ROLLING OF FLAT BILLETS CLAD WITH ZIRCONIUM-TIN ALLOY

Billet No.	Billet Type Tolerance (in.)	Origin of Uranium	History of Core Material	Preparation		Cladding Billet Reduction/Pass	Reduction (Accumul.)		Rolling Temp.		Passes Per Reheat		Plate Eval.		Cladding Dimensions			Significant Variable	Remarks	Results
				Core	Jacket		Gamma	Alpha	Gamma	Alpha	Gamma	Alpha	Bond	Dimens. Surface	Ave.	Ave. Dev.	Range of Dev.			
45	M.P.F.-P.W. .002 x .002 x .004	4D683	60% R.; R.M.S.	M.P.	V.B.	2-1/2 to 10%	12-1/2%	88%	840 °C	635 °C	2	2	B	C	Plate very irregular. No measurements obtained.			2-1/2% reduction/pass in γ range with total γ reduction of 12-1/2%, reheated every other pass.	U badly segregated throughout plate & extruded at edges.	Zr-Sn to U bond fair but no bond of Zr-Sn to Zr-Sn at edges.
46	M.P.F.-P.W. .002 x .002 x .004	4D679	60% R., R.M.S.	M.P.	V.B.	5 to 10%	45%	71%	840 °C	635 °C	2	2	C	C	No measurements obtained.			5% reduction/pass in γ range with total γ reduction of 45%, reheated every other pass.	U very badly extruded at edges and ends on account of failure of Zr-Sn to bond to Zr-Sn.	
47	M.P.F.-P.W. .002 x .002 x .004	4D679	60% R., R.M.S.	M.P.	V.B.	Billet broke open on first pass of 5% reduction at 840 °C.				840 °C			C	C				Billet rolled bare. (Without a steel can.)	Welded Zr jacket on flat billet does not offer sufficient restraint to permit rolling without steel can.	
48	M.P.F.-P.W. .002 x .002 x .004	4D679	60% R., R.M.S.	M.P.	V.B.*	2-1/2 to 10%	13-1/2%	88%	840 °C	635 °C	1	2	A	C	13.6 mils	1.70	12.4	Same as 45 except billet heated every pass during γ rolling.	U badly segregated throughout plate. Some bonding at plate edge.	Zr-Sn formed satisfactory bond to U core but edge bond was discontinuous.
49	M.P.F.-P.W. .002 x .002 x .004	4D683	60% R.; R.M.S.	M.P.	V.B.	5 to 10%	None	90%		635 °C		2	B	A	15.3 mils	2.14	14.3	90% reduction in α range.	Light segregation of U noted on autoradiograph. Plate surface very smooth.	Uniform plate with fair bond and good surface results from a rolling but cladding thickness not uniform.
50	M.P.F.-P.W. .002 x .002 x .004	4D684	60% R.; R.M.S.	M.P.	V.B.*	5 to 10%	30%	85%	840 °C	635 °C	1	2	B	C	14.8 mils	1.75	18.1	5% reduction/pass in γ range with total γ reduction of 30%, reheated every pass.	Same as 45.	Same as 45.

*Vacuum Anneal one hour at 1000 °C.

DEVELOPMENT OF ZRCLAD URANIUM PLATES FOR TESTING IN ANL LARGE SCALE HEAT THRU-PUT LOOP

Billet No.	Billet Design	Origin of Uranium	History of Core Material	Preparation		Cladding Billet Reduction/Pass	Total Reduction (Accumul.)	Rolling Temp.	Passes Per Reheat	Bonding Eval _g	Cladding Surface & Dimensions	Significant Variable	Remarks	Results
				Clad	Core									
29	Type A Loop-Plate P.W.	---	50% R. -R.M.S.	V.B.	M.P.	1.8% 4 to 10%	7.5% 90%	840°C 635°C	1 3	C	C	Billet designed for increased electric conductivity of ends, by increased cross-section of Zr.	Steel inserts in billet punctured can during rolling. Rolling gave spread = 27%.	Cladding surface unacceptable.
30	Type B Loop-Plate P.W.	---	50% R. -R.M.S.	V.B.	M.P.	3% 7 to 10%	11% 90%	840°C 635°C	1 3	B	B	Billet designed for distributed electric conductivity at ends, core tapered	Rolled satisfactorily. Rolling gave spread = 14%.	Plate was satisfactory.
35	Type B	---	50% R. -R.M.S.	V.B.	M.P.	6 to 10%	55%	840°C	2		B	Same as 30.	Plate 35 cracked at at edges - probably due to tungsten in billet welds. Spread = 22%.	Plate 35 unsatisfactory.
36	Loop-Plate P.W.					10%	88%	635°C	2					Plate 36 satisfactory.
51	Type B	4D692	50% R. -R.M.S.	V.B.	M.P.	2.5%	10%	840°C	1		A	Ti-namel can-two	Ti-namel and/or two	All plates suitable
52	Loop-Plate					6 to 10%	90%	635°C	2			piece can design.	piece can design	for pre-testing to
53	P.W.											Billet designed	restrains spread	qualify for heat
54												for distributed	in rolling.	thru-put tests.
55												electrical cond.	Spread = 5%.	
												Tapered core.		

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Table XIII

AUTOCCLAVE CORROSION TEST⁽¹⁾ RESULTS FOR ZRCLAD URANIUM PLATES

Plate No.	Nominal Cladding Thickness (in.)	Manufacturing Specs. in Table No.	Special Plate Characteristic	Notes on End Seals	Autoclave Exposure ⁽²⁾ and Results ⁽³⁾						
					170°C 24 hours	170°C 720 hours	210°C 24 hours	250°C 24 hours	250°C 120 hours	250°C 286 hours	330°C 24 hours
4	0 010	III	M.P.F. welded before rolling. Hot rolled surfaces.	Plate sheared to 24", exposed ends were etched & sealed by welding with Zr-3% Ni filler metal.	No effect	Small amount of white corr. prod. on weld seals.	---	No change	---	Weld seal failed at one end of plate.	Discontinued
5	0 010	III	M.P.F. welded before rolling. Hot rolled surfaces.	Same as 4.	Weld seal failed at one end of plate.	Discontinued after 120 hrs at 170°C					
5 welded	0 010	III	M.P.F. welded before rolling. Edge trimmed and rewelded after rolling. Hot roll surface.	Same as 4.	Slight red deposit on cladding.	Small amount of white corr. prod. plus 4 red spots on one end.	---	No change	---	No change	Cladding ruptured adjoining weld on edge & peeled.
6	0 010	III	M.P.F. billet, evacuated, not welded. Depends on bonding for edge seal. Hot roll surface.	Same as 4.	Cladding ruptured, apparently at edges.	Discontinued					
7	0.025	III	M.P.F. welded before rolling. Hot roll surface.	Same as 4.	End seal split.	Discontinued					
8	0 016	III	M.P.F. welded before rolling. Hot roll surface.	Same as 4.	Light, grayish deposit, probably corr. prod. from other sample in autoclave.	Small amount of white corr. prod. on welds.	---	No change	---	No change	White corr prod. on pre-rolling welds. Gray corr. prod. on entire surface.
11	0 010	IV	Cylinder billet. Hot roll surface.	Same as 4.	Same as 8.	Same as 8.	No change	No change	No change	No change	Same as 8.
12	0 012	IV	Cylinder billet. Hot rolled & cold finished.	Same as 4.	Same as 8.	Same as 8.	No change	No change	No change	No change	Same as 8.

Notes: ⁽¹⁾Plates were tested in untreated water with resistivity ranging from 350,000 ohms to 83,000 ohms. The only circulation occurred as a result of baffling and heater location in the autoclave.

⁽²⁾In series "A" the autoclave was decontaminated after 432 hours and testing was resumed with relatively pure water. Plates were vapor blasted and etched with 50% HNO₃-5% HF at this point.

⁽³⁾Since the purpose of these tests was to detect leakages in cladding, edge seals, and end seals the remarks do not refer to corrosion of the zirconium unless specifically stated.

⁽⁴⁾The principal reason for Series B was to test end sealing methods. All plates were rolled with a final zirconium extension of the core equal to 5". Weld seal technique was to etch the core to a depth of 1/16" more or less, and to fill the cavity with Zr-3% Ni alloy weld metal. In some cases plates were cut with the zirconium end extension at one end of the sample, in which case plates were tested with the end in the natural rolled condition, or with the end trimmed about 3" from end of core, or with the end trimmed and rewelded.

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Table XIII

(Cont.)

AUTOCLAVE CORROSION TEST⁽¹⁾ RESULTS FOR ZRCLAD URANIUM PLATES

Plate No.	Nominal Cladding Thickness (in.)	Manufacturing Specs. in Table No	Special Plate Characteristic	Notes on End Seals	Autoclave Exposure ⁽²⁾ and Results ⁽³⁾						
					170°C 24 hours	170°C 720 hours	210°C 24 hours	250°C 24 hours	250°C 120 hours	250°C 286 hours	330°C 24 hours
25	0.005	III	M.P.F. box type jacket welded before rolling. Cold finished.	Plate cut 24" long. One end sealed by weld technique. Other end, Zr trimmed and rewelded.	No effect	---	No effect	No effect	---	---	---
26a	0.025	III	Same as 25.	Plate cut 24" long. One end sealed by weld technique. Other end, Zr trimmed and rewelded.	No effect	Discontinued					
26b	0.025	III	Same as 25.	Plate cut 24" long. One end sealed by welding technique. Other end Zr trimmed & tested with out further preparation.	No effect	---	No effect	No effect	Small amount of white corr. prod. on welds. Slight corr. of Zr surfaces.	---	---
27a	0.010	III	M.P.F. press welded jacket. Cold finished.	Same as 26a.	No effect	---	No effect	No effect	Same as 26b.	---	---
27b	0.010	III	Same as 27a.	Same as 26b.	No effect	---	No effect	No effect	Same as 26b.	---	---
28	0.005	III	Same as 27a.	Same as 25a.	Failed. Defect in cladding was apparent cause of failure.						
42	0.010	X	Same as 27a except U-2 w/o Zr alloy core.	Plate cut 22" long. Both ends sealed by welding technique.	No effect	---	No effect	No effect	Same as 26b.	---	---
43a	0.010	III	M.P.F. press welded jacket.	Plate cut 22" long. One end sealed by welding technique. Other end, Zr trimmed & tested without further preparation.	No effect	---	No effect	No effect	Same as 26b.	---	---
43b	0.010	III	Same as 43a.	Plate cut 22" long. One end sealed by welding. Other end left as rolled.	No effect	---	No effect	No effect	Same as 26b.	---	---
51 52 53 54	0.010 in center sections core tapers to 0 at ends	XII	Tapered core thermal loop plate. Press welded. Cold finished. Zr to Ni to Cu ends on each plate.	Full length plates. Roll bonds form all seals.	No effect	---	No effect	No effect	Same as 26b. Zr-Ni weld on plate 51 failed. U core not exposed.	---	---

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Table XIV

DIMENSIONAL CHANGES NOTED IN SAMPLES OF CLAD
PLATE SUBJECTED TO THERMAL CYCLING

Specimen No.	Treatment	Original Size (in)	Growth on 250 Cycles	Approx. % Growth	Growth Coefficient K ⁽¹⁾	Degree of Warp
A	Rolled, (2) B.T. (3)	L = 2.245 W = 2.593 T = 0.112	L = +.001 W = .000 T = +.001	L = Nil W = Nil	L = Nil W = Nil	Very slight
B	Rolled, B.T. and annealed	L = 2.238 W = 2.580 T = 0.111	L = .000 W = -.001 T = +.001	L = Nil W = Nil	L = Nil W = Nil	Very slight
C	Rolled, B.T. and annealed, edges removed.	L = 2.238 W = 2.017 T = 0.111	L = +.006 W = +.006 T = .000	L = +0.27 W = +0.3	L = +10 W = +12	Slight
D	Rolled, edges removed, B.T., annealed.	L = 2.225 W = 1.967 T = 0.111	L = +.006 W = -.017 T = +.003	L = +0.27 W = -0.87	L = +10 W = -34	Moderate
E	Rolled, B.T., annealed edges and cladding removed.	L = 2.239 W = 2.047 T = 0.074	L = +.015 W = +.003	L = +0.65 W = +0.15	L = +26 W = +3	Severe
F	Rolled, edges and cladding removed, B.T., annealed.	L = 2.260 W = 2.004 T = 0.070	L = +.016 W = -.016	L = +0.7 W = -0.78	L = +28 W = -31	Severe
G	As rolled	L = 2.259 W = 2.534 T = 0.111	L = +.016 W = -.040	L = +0.7 W = -1.6	L = +28 W = -63	Moderate plus bumping
H	As rolled, edges removed	L = 2.257 W = 1.977 T = 0.110	L = +.034 W = -.040	L = +1.5 W = -2.0	L = +59 W = -79	Severe plus bumping
J	As rolled, edges and cladding removed	L = 2.260 W = 2.023 T = 0.0735	L = +.020 W = -.003	L = +0.9 W = -0.15	L = +35 W = -3	Very severe plus bumping

250 cycles between 100°C and 550°C

10 minute heating time

20 minute cooling time

$$(1) K = \frac{1}{N} \ln \left(\frac{L}{L_0} \right) \cdot 10^6 \text{ in microinches/inch/cycle}$$

(2) Roll bonded by 90% reduction at 635°C.

(3) B.T. = beta treated. (2 minutes at 725°C, water quenched)

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Table XV

BEND TEST DATA

Billet No.	Cladding Material		Core Normal Uranium Remelted Scrap	Rolling Temp. °C	Can Material	Angle of Rupture	
	Billet No.	Billet Hardness				1/8" radius	1/16" radius
5	Crystal Bar Zr AM #18 & 19		4D-663	840 635	C-1020 Carbon Steel	28° - 32°	30° - 34°
11	Crystal Bar Zr AM #26	Rockwell B-40	5D-744	840 635	Armco Iron	180° (No rupture)	100° - 101°
30	Crystal Bar Zr AM #48	Rockwell B-2		840 635	C-1020 Carbon Steel	67° - 74°	59° - 65°
49	Bu of Mines No. S-4044 Sn		4D-683	635	C-1020 Carbon Steel	32° - 39°	31° - 32°
65	Crystal Bar Zr AM #48	Rockwell B-2	803	840 635	C-1020 Carbon Steel	94° - 95°	78° - 81°
66	Crystal Bar Zr AM #48	Rockwell B-2	4D-683	840 635	C-1020 Carbon Steel	69° - 74°	65° - 66°
78	Crystal Bar Zr AM #48	Rockwell B-2	5D-766	635	C-1020 Carbon Steel	89° - 90°	74° - 79°
79	Crystal Bar Zr AM #48	Rockwell B-2	4D-684	635	C-1020 Carbon Steel	84° - 87°	75° - 78°
82	Crystal Bar Zr AM #67	Rockwell B-66	5D-804	660	Ti-namel Steel	180° (No rupture)	86° - 87°
83	Crystal Bar Zr AM #67	Rockwell B-66	4D-715	615	Ti-namel Steel	88° - 98°	76° - 82°
84	Crystal Bar Zr AM #67	Rockwell B-66	4D-679	640	Ti-namel Steel	180° (No rupture)	93° - 94°
85	Crystal Bar Zr AM #67	Rockwell B-66	5D-801	640	Ti-namel Steel	180° (No rupture)	100° - 107°
89	Bu of Mines Arc Melted Sponge		5D-880	630	Ti-namel Steel	60° - 68°	59° - 60°
90	(Cladding removed from U core before testing)		5D-880	620	Ti-namel Steel	180° (No rupture)	94° - 104°

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Table XVI

TYPICAL CHEMICAL ANALYSES FOR ZIRCONIUM AND URANIUM

Material	Billet Number	C	N	Al	Fe	Mg	Mn	Ni	Pb	Si
U	64	545	14/21	10	30	1	5	10	1	20
U	69	245	47/43	10	40	5	3	10	1	20
U	70	670	<10	5	100	1	3	10	30	30
U	72	555	22/14	10	300	1	3	10	5	30
U	74	810	42/43	10	40	1	3	10	<1	30
U	75	1015	12	10	200	1	3	20	5	30
U	78	620	32/28	10	100	1	3	10	2	30
U	81	1200	<10	10	150	1	3	20	7	30
	ANL Ingot No.	C	N	Al	Fe	Mo	Cr	Cu	Ni	
Zr (Arc-Melt. Gr. III Crystal Bar)	5T	350	168	50	500	<10	10	10	70	
	B	385	110	100	500	<10	5	10	70	
		C	N	Al	Fe	Cu	Mg	Mn	Pb	Si
Zr (Arc-Melt Bu. of Mines Sponge)	Typical	100/250	20/120	50	800/2000	30/100	50	10/20	50	20

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FIGURE 1 Bend Test Fracture - Zrclad Uranium

Figure 1a - Good Bonding. Zrcladding and the uranium core metal broke as a single piece.

Macro No. 11,946

2X

Figure 1b - Poor Bonding. Zrcladding separated from uranium core.

Macro No. 11,947

2X

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FIGURE 2. Modified Picture Frame Billet Assembly

FIGURE 3. Cylinder Billet Assembly

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FIGURE 4. Steps in Producing Zr-Clad Plates from Flat Billets and from Cylinder Billets

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FIGURE 5. Cladding Distribution in a Section of Plate No. 11, Rolled from a Cylindrical Billet in Flat Rolls

Avg. Clad Thickness based on
80% of width = 10 mils
Avg. Deviation = 7.3 %
Max. Deviation = 22 %

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The image displays two diamond-shaped objects side-by-side. The object on the left is dark grey with a very rough, irregular, and frayed edge, resembling a piece of coarse fabric or a rough-cut stone. The object on the right is also dark grey but has a much smoother, more regular, and polished edge, resembling a high-quality gemstone or a smooth piece of material. Both objects are set against a plain white background.

Approx. 1-1/3X

FIGURE 7 Cylinder Billet Rolled in Open Square Passes.

Macro section of Billet #37 after rolling in open square passes to 1" x 1" bar. The slight diamond shape conforms to the shape of the roll groove. Note folds in each corner and the irregular distribution of Zirconium.

[illegible]

50

FIGURE 8 Plate Rolled from Rough Rolled Square

Macro No. 13,244

3X

Macro section of a piece of flat rolled plate from Billet #37 which was previously rolled to 1" x 1" square in open-square passes (see Figure 7). Note the occurrence of irregular cladding distribution.

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FIGURE 9 Steel Can Designs for Flat or Modified Picture Frame Billets

FIGURE 9a Cross Section of Fabricated Can

This design depends upon the section "A" of weld metal at the sides of the billet to restrain lateral spread in rolling.

FIGURE 9b Cross Section of Two-piece Machined Can

This design depends upon the strength of the section at "A" to restrain lateral spread in rolling, and is superior to the fabricated can in this respect.

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FIGURE 10 Decanning of Hot Rolled Billet

FIGURE 11 Components of a Modified Picture-Frame Type Billet Ready for Assembly.

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FIGURE 12 Components of Modified Picture Frame Type Billet assembled in press ready to be welded with inert-gas shielded arc.

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graph TD
    subgraph STEEL_STORAGE [STEEL STORAGE]
        S1[Bars - 1/4" x 3" to 1/4" x 1 1/2"]
    end
    subgraph ZIRCONIUM_STORAGE [ZIRCONIUM STORAGE]
        Z1[Sheet - 1/8" | Plate - 1/2"]
    end
    subgraph URANIUM_STORAGE [URANIUM STORAGE]
        U1[Bars - 1 1/8" x 2" to 1 1/8" x 5"]
    end

    S1 -- "Side Plugs" --> PS[POWER SAW  
(cut lengths)]
    S1 -- "End Plugs" --> PS
    PS --> CS[CAN SUB ASS'BLY]

    S1 -- "Cores" --> SH[SHARP]
    SH --> BG[BLANCHARD GRIND]
    BG --> BSA[BILLET SUB ASS'BLY]

    Z1 -- "Jacket Sides" --> V[B]
    Z1 -- "Jacket Covers" --> V
    Z1 -- "End Plugs" --> PS
    Z1 -- "Cores" --> PS
    PS --> CS
    PS --> M[Mill or PRECISION CUT-OFF]
    M --> SH
    SH --> BG
    BG --> BSA

    U1 --> BSA

    CS --> FA[FINAL ASSEMBLY]
    BSA --> FA

    FA --> HR[HOT ROLLING]
    HR --> P[PICKLING  
(con stripping)]
    P --> S[Shear  
(Trimming)]
    S --> GF[GOLD FINISHING]
    GF --> E[ELEMENT ASSEMBLY]

    S --> ES[END SEALING]
    ES --> E
  
```

The flowchart illustrates the manufacturing process for nuclear fuel elements, starting from three parallel material storage paths and converging into a final assembly and finishing process.

STEEL STORAGE
 Bars - $\frac{1}{4}" \times 3"$ to $\frac{1}{4}" \times 1\frac{1}{2}"$
 Side Plugs
 End Plugs
 POWER SAW (cut lengths)
 BROACH (bevel & size)
 CAN SUB ASS'BLY

ZIRCONIUM STORAGE
 Sheet - $\frac{1}{8}"$ | Plate - $\frac{1}{2}"$
 Jacket Sides
 Jacket Covers
 End Plugs
 Cores
 MILL or PRECISION CUT-OFF
 SHAPER
 BLANCHARD GRIND
 BILLET SUB ASS'BLY

URANIUM STORAGE
 Bars - $1\frac{1}{8}" \times 2"$ to $1\frac{1}{8}" \times 5"$
 Cores
 BILLET SUB ASS'BLY

Final Assembly and Finishing
 CAN SUB ASS'BLY
 BILLET SUB ASS'BLY
 FINAL ASSEMBLY
 HOT ROLLING
 PICKLING (con stripping)
 SHEAR (Trimming)
 GOLD FINISHING
 END SEALING
 ELEMENT ASSEMBLY

FIGURE 13 Process Flow Sheet for Production of Zrclad Uranium Plates

FIGURE 14. Cladding distribution on Both Sides in a Transverse Section of Modified Picture Frame Billets Rolled to Partial Reduction

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FIGURE 15a. Tapered Core Heat-Thru-Put Test Plate

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Ti-namel Steel Can
2 required

End Plugs
2 required

FIGURE 15b. Billet Assembly - Heat-Thru-Put Test Plate

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FIGURE 16 Corrosion Tested Plate

Views of plate 6 which failed during an exposure for 24 hours at 170°C. This plate was manufactured by the modified picture frame technique; the zirconium jacket was not welded before rolling, but the billet was evacuated and the can was made from vacuum annealed C-1020 steel. Failure was not typical of the end seal type failure. The conclusion was that Zr to Zr bonds were inadequate.

FIGURE 17 Corrosion Tested Plates

Plates 11 & 12 manufactured by the cylinder billet technique, and plate 8 by the modified picture frame technique. These plates survived 720 hours at 170°C, 286 hours at 250°C, and 24 hours at 330°C. It is significant that all six (6) end seals survived without indication of failure.

FIGURE 18 Corrosion Tested Plates

Views of a plate which survived autoclave exposure for 720 hours at 170°C, plus 286 hours at 250°C, and failed within an additional 24 hours at 330°C.

This plate was manufactured by the modified picture frame technique. After rolling the plate edges were trimmed and rewelded with inert gas shielded arc in air. Considering quality of the zirconium and methods of welding these results might be considered encouraging.

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Micro No. 13,746

1000X

Etchant 5 HF-AgNO₃ (light etch)

FIGURE 19 Microphoto at Interface in Plate No. 79.

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63

Micro No. 12,804

500X

Electrolytic Polish

FIGURE 20a Void Near the Center of a Zrclad Plate.

Micro No. 12,812

500X

Electrolytic Polish

Figure 20b Voids at the edge of a Zrclad Plate.

FIGURE 20 Micrographs showing voids at the bond interface on Zrclad plates.

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FIGURE 21 Macrosections in Hot Rolled Clad Plate

Sections taken at 7 inch intervals along the length of one plate. Notice the uniformity of width.

65

A

B

C

D

FIGURE 22 (A,B,C, & D) Autoradiographs showing typical defects in clad plates.

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E

F

FIGURE 22 (E & F) Autoradiographs showing defect in clad plate and plate with uniform core distribution and cladding thickness.

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Cycled in the as-rolled condition. Specimen G has the cladding intact; Specimen H has the edge cladding removed; Specimen J has edge and surface cladding removed.

Cycled in the β treated condition. Specimens A & B have the cladding intact; Specimens C & D have the edge cladding removed; Specimens E & F have edge and surface cladding removed. Cladding was removed from C & E after β treatment, and from D & F before β treatment.

FIGURE 23 Zrclad Uranium Plates - Thermal Cycled.
 Samples of Zrclad normal U plate roll bonded at 635°C.
 Cycled 250 times between 100°C and 550°C, with 10 minute
 heating time and 20 minute cooling time.

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FIGURE 24. Specimen for Tensile Test of Bond Strength in Clad Plates.

FIGURE 24-a Welded Assembly

FIGURE 24-b Machining Detail

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FIGURE 25 Microstructures of Bond Test Specimens.

Micro No. 13,201 150 X Electrolytic Etch

FIGURE 25a Recrystallization of cladding and core material at bond interface due to overheating while welding.

Micro No. 13,200 150X Electrolytic Etch

FIGURE 25b Zirconium stud welded to cladding without affecting the cladding to core bond interface.

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FIGURE 26 16" x 24" Rolling Mill. Control Panel is shown on left.

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FIGURE 27. 16 x 24 Roughing Set Roll (Open Square Passes)

FIGURE 28. 16 x 24 Roughing Set Roll (Oval-Edge-Oval Passes)

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FIGURE 29 5-3/4" x 16" x 12" Rolling Mill. Bliss 4-high control panel is shown on right.

FIGURE 30 Electric Muffle Furnace. Muffle is 18" wide, 8" high, 72" long.

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FIGURE 31 Pot Type Lead Furnace 10" x 14" x 84"

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FIGURE 32 Waterbury-Farrel Roll Straightener, 3-1/2" x 15", For flattening plates.