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CORE SHAPE OF FUEL ELEMENTS CLAD WITH ZIRCONIUM ALLOY

by

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For The Atomic Energy Commission

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Chief, Declassification Branch

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ABSTRACT

The processing of [redacted] fuel elements clad with zirconium-tin alloys is described.

Satisfactory core end shapes were obtained with a wide range of tin contents in the core alloy by suitably adjusting the roll-cladding temperature. For a zirconium-2.5 tin alloy clad, the tin content in the core alloy could vary from 2 to 5 wt % depending upon the uranium content chosen, if the roll-cladding temperature were adjusted at the optimum temperature, between 1400 and 1675 F. Optimum results were obtained with a zirconium-4.2 uranium-2.5 tin alloy core prepared from either crystal-bar or sponge zirconium roll clad at 1425 F. When the uranium content of the sponge-zirconium core was increased to 5.0 wt % and the clad was sponge zirconium-2.5 tin alloy, the tin content of the core had to be raised from 2.5 to 3.0 wt %.

When a sponge zirconium-1.5 tin-0.12 iron-0.10 chromium-0.05 nickel alloy clad was used, either 1.5 or 2.0 wt % tin was required in the core of fuel elements containing 4.6 wt % uranium, if the roll-cladding temperature were in the range of 1425 to 1500 F. Optimum results with 1.5 wt % tin in the core were obtained when roll cladding was conducted at 1450 F.

In general, the core should contain the same amount of tin as the clad, with a permissible variation of ± 0.5 wt % tin. There is an added advantage to this because the core alloy can be made from the clad alloy simply by adding uranium. As the uranium content of the core is increased above about 4 wt %, the tin content in the core should be increased above the amount in the clad.

There was good agreement between optimum roll-cladding temperatures, determined experimentally, and corresponding temperatures, predicted from hot-hardness and roll-pressure data. Hot-hardness and roll-pressure data can, therefore, be used to predict satisfactory roll-cladding temperatures.

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INTRODUCTION

Unalloyed crystal-bar zirconium was used as the cladding material for the zirconium-uranium fuel elements. Plans called for the use of sponge zirconium which is much less expensive and more readily available than crystal-bar zirconium. The sponge zirconium was to be alloyed with tin for better resistance to corrosion, and used for the clad.

Fuel elements clad with this alloy developed a marked irregularity in thickness at the ends of the core when fabricated.

The purpose of the work reported here was to develop a fabrication technique which minimizes core irregularities.

In the early work, the cladding alloy was sponge zirconium containing 2.5 wt % tin. This was later replaced by an alloy of sponge zirconium containing 1.5 tin-0.12 iron-0.10 chromium-0.05 nickel which had improved corrosion resistance.

Although U. S. Bureau of Mines sponge zirconium was to be used, suitable alloys were not available at the start of this investigation. Preliminary work was done with crystal-bar zirconium alloys, and the experience gained was used in planning subsequent tests with sponge zirconium alloys.

EXPERIMENTAL PROCEDURES

Materials

Because sponge zirconium was not available when the program was initiated, Foote Mineral and WAPD crystal-bar zirconium were used. When sponge zirconium became available, it was supplied as zirconium-2.5 tin alloy arc melted once by the Bureau of Mines at Albany, Oregon. It was remelted before use in fuel elements. This 2.5 wt % tin alloy is now referred to as Zircaloy 1.

The sponge zirconium-1.5 tin-0.12 iron-0.10 chromium-0.05 nickel clad alloy is called Zircaloy 2. It was prepared by arc melting Q sponge twice, with the appropriate additions of chromium, iron, nickel, and tin.

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Clad and Core Compositions

Clad Alloys

In work done prior to the present investigation, zirconium - 0 to 5 wt % tin alloys had been used. Because of the difficulty of fabricating the higher-tin alloys, zirconium-2.5 tin alloy, Zircaloy 1, was chosen as the composition of the clad. Most of the work reported here was done with this clad composition.

Toward the end of the investigation, the clad was changed to Zircaloy 2 which has greater corrosion resistance than the zirconium-2.5 tin alloy. Only one series of fuel elements was clad with Zircaloy 2.

Core Alloys

Uranium contents studied in the core were: 3.8, 4.2, 4.6, and 5.0 wt %. In the majority of the work, a 4.2 wt % uranium alloy was used, because this represented, at the time, the best estimate of core composition.

Previous work^{(1)*} on roll cladding fuel elements (and subsequent data from hot-hardness and roll-pressure studies) showed that the addition of tin to the zirconium clad made the clad harder and less plastic than the zirconium-uranium core at roll-cladding temperatures. These differences resulted in the formation of a bulbed or elongated core end. To obtain equal plasticity, tin also was added to the core.

In the present work, tin contents in the cores ranged from 0 to 5 wt %. Cores with 4 and 5 wt % tin were difficult to fabricate and, in most of the work, cores with 3 wt % tin or less were investigated.

Processing Fuel-Element Packs Before Roll Cladding

Description of Fuel Elements

The fuel elements consisted of two cover plates and a picture frame of zirconium-tin alloy and a core of zirconium-uranium alloy which fitted into the cavity of the picture frame. The cover plates were 0.135 in. thick by 3.126 in. wide by 5.750 in. long. The picture frame had the same width and length as the cover plates but it was only 0.103 in. thick. A core 0.103 in.

* See References.

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thick by 1.990 in. wide by 3.775 in. long fitted into the window of the picture frame. The components were face milled with a single-point cutter. Tolerances were ± 0.002 in.

To protect the fuel-element pack from oxidation during roll cladding, it was enclosed in a steel jacket. The jacket consisted of a cavity, end milled in a steel plate, into which the fuel-element pack was inserted. A single steel cover was then welded over the open face of the steel jacket. The overall dimensions of the steel jacket were 0.515 in. by 5-9/16 by 9-1/4 in. Cover plates were 0.071 in. thick.

A steel tube, extending into the cavity, was welded to one end of the steel jacket. This tube was used to evacuate the assembly before sealing under vacuum. Because it is difficult to obtain a leak-tight weld around the tube at roll-cladding temperatures, the integral evacuation tube used by WAPD is more satisfactory. The integral tube is machined directly from the body of the steel jacket.

Most of the jackets were made of low-carbon steel, SAE 1020. For comparison, a few jackets were made from Ti-Namel steel. This is a low-carbon, low-nitrogen steel used by WAPD to prevent contamination of the zirconium fuel element by nitrogen from the steel. The type of steel did not appear to affect the shape of the core end.

Cleaning Fuel-Element Components

To obtain a bond between the various zirconium components, it is necessary to clean the parts thoroughly before assembly. The zirconium components were scrubbed with a commercial detergent, Alconox, and then thoroughly rinsed with hot water. They were dried in dust-free air and handled with rubber gloves. The steel jackets were degreased with trichloroethylene, washed with Alconox, and rinsed in hot water.

Evacuation and Sealing of Packs

After cleaning, the fuel element was assembled and placed in the steel jacket. The jacket was clamped between copper plates while the steel cover plate was arc welded to the steel picture frame. The copper plates prevented overheating of the fuel-element components. Overheating must be avoided because oxidation of the mating surfaces prevents bonding during roll cladding. The weld joint was tested for leaks by immersing the pack in water while maintaining a pressure of 40 psi of argon inside the pack.

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The welded packs were then placed on a vacuum manifold and evacuated to a pressure of less than 10 microns. Evacuation was continued for 12 hr or overnight when feasible. The pack was sealed while still under vacuum by heating the evacuation tube and hammering the tube flat. The flattened portion was cut in half with an oxygen-acetylene torch. Sealed in this manner, the packs were ready for roll cladding.

Fabrication of Fuel Elements

Selection of Trial Fabrication Temperature

The first survey to determine the proper roll-cladding temperature covered the temperature range 1400 to 1675 F. The upper temperature was limited by the formation of a zirconium-iron eutectic at about 1700 F between the zirconium clad and the steel jacket. Consequently, the highest roll-cladding temperature used was 1675 F. Local overheating occasionally caused sticking at spots between the clad and the steel jacket.

The lower temperature was limited by the plasticity of the fuel-element components and by the necessity of obtaining a metallurgical bond between the mating surfaces of the fuel-element components. It was first believed that a strong and corrosion-resistant bond might not be obtained when roll cladding was conducted at 1500 F or lower. A diffusion treatment of 1 hr at 1625 F was inserted into the rolling schedule before the last pass through the mill to allow the impurities to diffuse away from the bond line. When good bonds were obtained at temperatures under 1500 F, the diffusion treatment was abandoned.

In addition, it was believed that phase transformations of the clad and core might influence the bonding of the fuel-element components and the shape of the core. Transformation temperature ranges for clad and core alloys were obtained from dilatometric data. These ranges were as follows:

Type of Zirconium	Type of Component	Composition, wt % (Balance Zr)	Transformation Temperature Range, F	
			Lower Limit	Upper Limit
Crystal bar	Core	3.7U	1435	1605
Ditto	"	3.7U + 2Sn	1500	1645
"	"	3.7U + 2.5Sn	1490	1650
"	"	3.7U + 3.0Sn	1525	1690
"	"	3.7U + 4.0Sn	1490*	1815*
"	"	3.7U + 5.0Sn	1580	1715
Crystal bar	Clad	2.5Sn	1600	1690
Sponge	"	2.5Sn	1600	1832

* This alloy had a very long transformation range. It was probably contaminated.

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It was considered desirable to avoid roll cladding in the transformation temperature range. However, in the first survey, one temperature was chosen within this range. Thus, temperatures were chosen above, within, and below the transformation range for the core.

Roll-Cladding Procedure

Fuel elements, sealed in evacuated steel jackets, were heated to the roll-cladding temperature in air. They were then given a 3 to 1 total reduction by rolling. A small number of fuel elements were rolled in 4 passes using equal reductions per pass, but 6 passes with equal per cent reduction were used in most cases. The fuel elements were heated for 30 min before the first pass through the rolls and were returned to the furnace for 20 min after each pass. When a diffusion treatment was used, the elements were held at 1625 F for 1 hour before the last pass.

After roll cladding, the steel jackets were stripped from the fuel elements. The fuel elements were reduced 10 per cent by cold rolling and, were then ready for inspection.

Inspection of Fuel Elements for Quality

Corrosion data will not be reported in detail here. Corrosion resistant bonds can be obtained consistently at the roll-cladding temperatures used, and most of the fuel elements made during this work had corrosion-resistant bond lines.

The principal objective of this work was to examine the shape of the core. To accomplish this, the fuel element was sectioned longitudinally, polished, and the shape of the core was examined at low magnification. The ends of the core were rated by a shape factor obtained by dividing the thickness of the core at the end by the average core thickness. Thus, a shape factor of 1.0 indicated a square end. Examples of core-end sections with various end-shape factors are shown in Figure 1.

A shape factor of 1.0 would be the ideal shape. If the shape factor were greater than 1.0, the clad over the ends would be thinner than the remainder of the clad and would result in a "hot spot" on the fuel element. Thus, shape factors greater than 1.0 are unacceptable. If the shape factor were less than 1.0, the end of the core would be tapered. A slight taper is permissible, but when taper is extreme, the core end may protrude into the cladding as in the core with a shape factor of 0.70 in Figure 1. In extreme cases, the bent core might be quite close to the outer surface of the clad.

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$f = 0.50$

$f = 0.70$

$f = 0.80$

$f = 0.90$

$f = 1.00$

$f = 1.05$

$f = 1.10$

$f = 1.20$

$f = 1.30$

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FIGURE 1. EXAMPLES OF CORE END SECTIONS WITH VARIOUS SHAPE FACTORS

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Thus, in practice, a shape factor of slightly less than 1.0 is desirable, so that normal scatter does not give a thick core end.

RESULTS

About 450 fuel elements were roll clad during this work. The results are presented in Figures 2 through 9, as graphs of shape factor as a function of roll-cladding temperature and tin content.

Crystal-Bar Zirconium Alloys

Data are presented in Figures 2 and 3 for fuel elements consisting of crystal-bar zirconium-2.5 tin clad and zirconium-3.8 uranium + tin cores. A shape factor of 1.0 was obtained with cores containing 2.5, 3, 4, and 5 wt % tin. Rolling temperatures required were 1500, 1525, 1650, and 1675 F, respectively. Although a shape factor of 1.0 was not obtained with a 2 per cent tin core, this core is satisfactory if it is roll clad in the range of 1400 to 1450 F. The zirconium-3.8 uranium core with no tin addition was unsatisfactory.

Although satisfactory core shapes could be obtained with cores containing 4 and 5 wt % tin, these cores were eliminated from further consideration because of difficulties in fabrication. Therefore, a more restricted range of core composition and rolling temperature was used in subsequent work. For cores with 4.2 wt % uranium, only 2, 2.5, and 3 wt % tin and a temperature range of 1400 to 1500 F were studied.

Crystal-bar zirconium cores containing 4.2 wt % uranium plus tin and clad with crystal-bar zirconium-2.5 tin alloy gave the data illustrated in Figure 4. A shape factor of 1.0 was obtained at 1400 F with a 2.5 wt % tin in the core. A temperature of 1450 F was optimum for a core containing 3 wt % tin. Although the core with 2 wt % tin did not produce a shape factor of 1.0 at any temperature in the range, it yielded an acceptable core shape when rolled at 1400 F.

Sponge-Zirconium Alloys

The material of greatest interest, of course, was sponge zirconium. On the basis of information gained with crystal-bar zirconium, the study was limited to cores containing 2.5 and 3.0 wt % tin and 4.2 wt % uranium, and

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FIGURE 3. EFFECT OF TIN CONTENT OF THE CORE AND ROLL-CLADDING TEMPERATURE ON THE SHAPE OF THE END OF THE CORE SECTION WHEN THE CORE CONTAINS FOOTE MINERAL CRYSTAL-BAR ZIRCONIUM -3.8 WEIGHT PER CENT URANIUM

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FIGURE 4. EFFECT OF ROLL-CLADDING TEMPERATURE ON THE SHAPE OF THE END OF THE CORE SECTION FOR FOOTE MINERAL CRYSTAL-BAR CORES CONTAINING 4.2 WEIGHT PER CENT URANIUM AND VARIOUS TIN CONTENTS

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FIGURE 5. EFFECT OF ROLL-CLADDING TEMPERATURE ON THE SHAPE OF THE END OF CORES HAVING DIFFERENT LEVELS OF TIN CONTENT; SPONGE CORES AND SPONGE CLAD

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FIGURE 6. EFFECT OF TIN CONTENT OF THE CORE AND ROLL-CLADDING TEMPERATURE ON THE SHAPE OF THE END OF THE CORE; SPONGE CORE AND SPONGE CLAD

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FIGURE 7. EFFECT OF ROLL-CLADDING TEMPERATURE ON THE SHAPE OF THE END OF CORES HAVING DIFFERENT LEVELS OF TIN CONTENT; SPONGE CORE AND SPONGE CLAD

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FIGURE 8. EFFECT OF TIN CONTENT OF THE CORE AND ROLL-CLADDING TEMPERATURE ON THE SHAPE OF THE END OF THE CORE, SPONGE CORE AND SPONGE CLAD

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FIGURE 9. EFFECT OF ROLL-CLADDING TEMPERATURE ON THE SHAPE FACTOR OF THE ENDS OF CORES HAVING TWO LEVELS OF TIN CONTENT

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a roll-cladding range of 1400 to 1600 F. The clad was Zircaloy 1, a sponge zirconium-2.5 tin wt % alloy. Data from these fuel elements are presented in Figures 5 and 6. A shape factor of 1.0 was not attained with 2.5 wt % tin in the core. However, satisfactory core shapes were obtained with this composition at the lower end of the temperature range from 1400 to 1450 F. The cores with 3.0 wt % tin gave a shape factor of 1.0 at about 1500 F.

Figures 7 and 8 present data from fuel elements containing sponge zirconium-5 uranium-tin cores clad with Zircaloy 1. Increasing the uranium from 4.2 to 5.0 wt % uranium stabilizes additional beta zirconium and makes the core more plastic than the clad. Consequently, higher tin contents and lower rolling temperatures were used. Cores containing 2.5 wt % tin were too plastic over the temperature range of 1350 to 1500 F. A shape factor of 1.0 was obtained at 1500 F with 3.5 wt % tin in the core. The core with 5.0 wt % tin was not sufficiently plastic over the temperature range 1400 to 1550 F.

The last group of fuel elements studied were clad with Zircaloy 2, which consisted of sponge zirconium-1.5 tin-0.12 iron-0.10 chromium-0.05 nickel. Cores were made from the clad alloy by adding 4.6 wt % uranium. Tin contents were adjusted to obtain 1.5 and 2.0 wt % tin in the core. Results of the examination of these fuel elements are summarized in Figure 9. Both of the core compositions could be used at approximately the same roll-cladding temperatures. However, the core with 1.5 wt % tin was preferable. It could be clad in the temperature range from 1425 to 1475 F, with optimum core configuration at 1450 F. If it were desirable to use 2.0 wt % tin in the core, the core can be roll clad in the temperature range of 1450 to 1500 F, with optimum core configuration at a temperature of 1475 F. A shape factor of 1.0 was obtained at 1450 F with 2.0 wt % tin in the core.

Sponge-Zirconium Clad and Crystal-Bar Zirconium Cores

A few fuel elements were roll clad, using crystal-bar zirconium-4.2 uranium + tin cores clad with Zircaloy 1. Cores studied contained 2.0, 2.5, and 3.0 wt % tin. All of them were too plastic in the temperature range of 1400 to 1500 F to match the clad. Possibly, a 4 wt % tin core would be satisfactory when rolled at 1425 F.

DISCUSSION OF RESULTS

Roll Cladding

Examination of the results of the general survey with crystal-bar zirconium showed that satisfactory core configuration can be obtained with a range of about 2 to 5 wt % tin in the core by suitably adjusting the roll-cladding temperature between 1400 and 1675 F. Combinations of tin content in the core and roll-cladding temperature to produce a shape factor of 1.0 are readily obtained from Figure 3.

Increasing the uranium content of the core from 3.8 to 4.2 wt %, stabilized additional beta zirconium and softened the core. The decrease in hardness can be compensated (1) by increasing the amount of tin in the core or (2) by decreasing the rolling temperature.

Comparison of results for crystal-bar and sponge-zirconium fuel elements showed that the same roll-cladding temperature range could be used for both types of zirconium. Cores containing zirconium-4.2 uranium-2.5 tin were roll clad with zirconium-2.5 tin alloy in the same roll-cladding temperature range from 1400 to 1450 F when either crystal-bar or sponge zirconium was employed. Dropping the tin to 1.5 wt % tin, as in Zircaloy 2, did not change the roll-cladding temperature when the tin content of the core was also reduced to 1.5 wt %.

Recommended Core Compositions and Roll-Cladding Temperatures

As pointed out in preceding sections, many combinations of core compositions and roll-cladding temperatures produced satisfactory results. However, the following combinations are recommended for use with the clad indicated.

Type of Zirconium in Clad and Core	Composition, wt % (Balance Zr)		Recommended Cladding Temperature, F
	Clad	Core	
Crystal bar	Zr-2, 5Sn	Zr-3, 8U-2, 0Sn	1425
Crystal bar	Zr-2, 5Sn	Zr-4, 2U-2, 5Sn	1425
Sponge	Zr-2, 5Sn	Zr-4, 2U-2, 5Sn	1425
Sponge	Zr-2, 5Sn	Zr-5, 0U-3, 0Sn	1425
Sponge	Zr-1, 5Sn-0, 12Fe- 0, 10Cr-0, 05Ni	Zr-4, 6U-1, 5Sn-0, 12Fe- 0, 10Cr-0, 05Ni	1450

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Increasing the tin content in the core by 0.5 wt % over that recommended or, in some cases, reducing it by 0.5 wt %, would still produce satisfactory results.

Comparison of Roll-Cladding Data With
Hot-Hardness and Roll-Pressure Data

Hot-hardness and roll-pressure data were obtained by other investigators on clad alloys and possible core alloys to predict roll-cladding temperatures. A comparison was made between roll-cladding temperatures obtained experimentally and the optimum temperatures predicted by hot-hardness and roll-pressure data. The roll-cladding temperature required to give a shape factor of 1.0 should correspond to the temperature at which the hot hardness of the clad and core are equal, and to the temperature at which they have the same resistance to deformation as determined by roll-pressure studies.

The diamond-pyramid hardnesses of various clad and core alloys were obtained at elevated temperatures with a vacuum hot-hardness machine. (2) These data are summarized in Figures 10, 11, and 12.

The temperatures at which the hardnesses of the clad and core were equal or similar were as follows for crystal-bar zirconium-3.8 uranium-tin core alloys and a crystal-bar zirconium-2.5 tin cladding alloy.

<u>Composition of Core, wt % (Balance Zr)</u>	<u>Predicted Roll-Cladding Temperature, F</u>	<u>Remarks Concerning Core</u>
3.8U	-	Too soft throughout entire temperature range.
3.8U + 2.0Sn	-	Too soft above 1400 F; possibly 1400 F could be used.
3.8U + 2.5Sn	1400-1500	Not very sensitive to temperature.
3.8U + 3.0Sn	1500	-
3.8U + 4.0Sn	1600	-
3.8U + 4.0Sn	-	Too hard throughout entire temperature range. Extrapolation of data would indicate 1625 F could be used.

Uranium stabilizes beta zirconium which is much softer than alpha zirconium, as seen in Figure 10. Since uranium stabilizes beta zirconium, uranium has a softening effect at some elevated temperatures.

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FIGURE 10. HARDNESS OF CRYSTAL-BAR Zr, Zr-Sn, AND Zr-3.8 WT % U-Sn ALLOYS AT ELEVATED TEMPERATURE

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FIGURE II. HARDNESS OF SPONGE Zr-Sn AND Zr-U-Sn ALLOYS AT ELEVATED TEMPERATURE

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FIGURE 12. INFLUENCE OF TEMPERATURE ON ROLL PRESSURE OF FOOTE MINERAL CRYSTAL-BAR Zr, Zr-Sn, AND Zr-3.8 WT % U-Sn ALLOYS

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On the other hand, tin stabilizes alpha zirconium. As seen in Figure 10, as more tin is added to the core, the core alloys become progressively harder over the entire temperature range of interest. With the addition of 4 wt % or more tin to the core, the core is harder than the clad over the entire temperature range of 1400 to 1600 F.

Hardness data plotted in Figure 11 indicated that sponge-zirconium cores containing 2.5 wt % tin and either 4.2 or 5.0 wt % uranium would be softer than sponge zirconium-2.5 tin clad over the temperature range from 1400 to 1600 F.

Roll-pressure studies⁽³⁾ were made to aid in selecting temperatures and compositions at which clad and core alloys would have the same deformation characteristics during roll cladding. Roll-load values were obtained on alloys by measuring the force between a pair of rolls during rolling at various temperatures. These data are presented graphically in Figures 12, 13, and 14.

The core composition and roll-cladding temperature at which the resistance to deformation is equal for a crystal-bar zirconium-2.5 tin cladding alloy and a crystal-bar zirconium-3.8 uranium-tin core are as follows.

<u>Composition of Core, wt %</u> (Balance Zr)	<u>Roll-Cladding Temperature, F</u>
3.8U + 2Sn	1400
3.8U + 2.5Sn	1460
3.8U + 3Sn	1520

A zirconium-3.8 uranium core alloy with no tin had far too little resistance to deformation to match the clad. If the uranium content is raised to 4.2 wt % in the crystal-bar zirconium alloys, as shown in Figure 13, a core with 2.5 wt % tin could be rolled at 1475 F, while cores with 4 and 5 wt % tin would require a rolling temperature in the range of 1600 to 1625 F.

The limited data on sponge-zirconium alloys are presented in Figure 14. A 4.2 wt % uranium core with the addition of 2.5 wt % tin was more readily deformed than the clad over the entire range of 1400 to 1675 F. A core with 5 wt % tin would be satisfactory at 1625 F.

Suitable roll-cladding temperatures determined by the various methods are summarized in Table 1. In general, agreement among the methods was qualitatively good. In particular, agreement for the 3.0 wt % tin cores containing both 3.8 and 4.2 wt % uranium was extremely good.

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FIGURE 13. INFLUENCE OF TEMPERATURE ON ROLL PRESSURE OF FOOTE MINERAL CRYSTAL-BAR Zr, Zr-Sn, AND Zr-4.2 WT % U-Sn ALLOYS

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FIGURE 14. INFLUENCE OF TEMPERATURE ON ROLL PRESSURE OF SPONGE Zr, Zr-Sn, AND Zr-4.2 WT%U-Sn ALLOYS

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TABLE 1. OPTIMUM ROLL-CLADDING TEMPERATURE DETERMINED BY EXPERIMENTAL ROLL CLADDING,
BY HOT-HARDNESS MEASUREMENTS, AND BY ROLL-PRESSURE STUDIES

Composition of Core, wt % (Balance Zr)	Type of Zirconium Used in Core and Clad ⁽¹⁾	Optimum Roll-Cladding Temperature, F		
		Experimental Roll Cladding	Hot-Hardness Data	Roll-Pressure Data
3.8U + 2Sn	Footo Mineral Crystal Bar	More plastic than the clad ⁽²⁾	Softer than the clad ⁽²⁾	1400
3.8U + 2.5Sn	Ditto	1500	1400-1500	1460
3.8U + 3.0Sn	"	1520	1500	1520
3.8U + 4.0Sn	"	1645	1600	-(3)
3.8U + 5.0Sn	"	1675	1625 ⁽⁴⁾	-(3)
4.2U + 2Sn	"	More plastic than the clad ⁽²⁾	1400	-(3)
4.2U + 2.5Sn	"	1400	-(3)	1475
4.2U + 3.0Sn	"	1450	1465	-(3)
4.2U + 4.0Sn	"	-(3)	-(3)	1625
4.2U + 5.0Sn	"	-(3)	-(3)	1610
4.2U + 2.5Sn	Sponge	More plastic than the clad ⁽²⁾	Softer than the clad ⁽²⁾	More plastic than the clad ⁽²⁾
4.2U + 3.0Sn	"	1500	-(3)	-(3)
4.2U + 5.0Sn	"	-(3)	-(3)	1625
5.0U + 2.5Sn	"	More plastic than the clad ⁽²⁾	Softer than the clad ⁽²⁾	-(3)
5.0U + 3.5Sn	"	1500	-(3)	-(3)

(1) All of the clad material contained 2.5 wt % tin.

(2) This condition existed over the entire temperature range studied.

(3) No data were obtained.

(4) This value was obtained by extrapolating the data obtained experimentally over the temperature range from 1400 to 1600 F.

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Some combinations of core composition and temperature did not produce a shape factor of 1.0 and, therefore, do not appear in Table 1. However, because a shape factor of slightly less than 1.0 is permissible, acceptable core-end shapes could be produced with them. For example, crystal-bar zirconium-2 tin cores, containing both 3.8 and 4.2 wt % uranium, produced satisfactory core-end shapes at 1400 to 1425 F. Also, the sponge zirconium-2.5 tin core, containing 4.2 wt % uranium, is satisfactory when clad with a sponge zirconium-2.5 tin alloy at 1425 F.

It is concluded that both hot-hardness data and roll-pressure data may be used satisfactorily to predict roll-cladding temperatures.

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