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AEC Research and
Development Report

The Development of Composite Control Rods for Water-cooled Power Reactors

W. E. Ray

October 15, 1957

Operated for the
United States Atomic
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THE DEVELOPMENT OF COMPOSITE CONTROL RODS
FOR WATER-COOLED POWER REACTORS

W. E. Ray

October 15, 1957

C. E. Weber

Authorized Classifier

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Date

Knolls Atomic Power Laboratory
General Electric Company
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CONTENTS

	<u>Page</u>
ABSTRACT	ix
ACKNOWLEDGMENT	x
INTRODUCTION	1
PROCEDURE	2
RESULTS AND DISCUSSION	10
SUMMARY AND CONCLUSIONS	25

ILLUSTRATIONS

<u>Figure No.</u>	<u>Title</u>	
1	Integrally rolled composite control rod blade, showing finish-machined dimensions (KS-25072) .	3
2	Components of welded composite control rod blade, showing finish-machined dimensions (except over-all length) (KS-25073)	4
3	Fabrication flow chart for composite control rod blades (KS-25074)	5
4	Stainless steel rolling containing composite control rod blade assembly with cover plates removed (KS-25075)	7
5	Irradiation capsule containing composite control rod test sample to be irradiated in contact with reactor coolant water (KS-17496)	7
6	Apparatus used in performing bend tests on both irradiated and unirradiated materials (KS-15277)	8

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
7	Integrally rolled composite samples before and after room temperature tensile testing (KS-16697)	11
8	Integrally rolled composite control rod blade with cladding machined to final thickness (KS-25076)	11
9	Samples from welded composite control rod blade assembly (KS-16645)	12
10	Small scale composite control rod blade prepared by rolling in a type 304 stainless steel pack at 1600°F (Reduction ratio 3/1) (KS-15925)	12
11	Ti-clad Hf rolled in stainless steel pack at 1600°F to 3/1 reduction (small scale) (KS-25077).	15
12	Hafnium-titanium bond made by hot rolling at 1600°F in stainless steel pack. Structure near outside radius of 80 degree bend made at room temperature 250X (KS-25078)	15
13	3.5 w/o B in titanium, titanium-clad (prepared by hot rolling at 1600°F in stainless steel pack - 20 degree bend at 650°F) (KS-25079)	16
14	Exposed ends of a composite control rod sample after autoclaving for 1000 hours in degassed, deionized water at 680°F (KS-25080)	16
15	Photomicrographs of titanium-clad, titanium 3.5 w/o Boron ¹⁰ dispersion material irradiated in capsule 28-29 (KS-16608).	21
16	Portion of irradiated titanium-clad, titanium 3.5 w/o Boron ¹⁰ dispersion near welded end closure (KS-25081).	22

TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page</u>
I	Roll pass sequence for composite control rod processing	6
II	The dimensions of three integrally rolled composite control rod blades	10
III	Dimensions of blade sections suitable for use in composite control rod blades of the welded type	13
IV	Bend test data obtained using titanium-clad sections from full-size integrally rolled composite plates	18

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ABSTRACT

The phrase "composite control rod" is used herein to describe a hafnium-tipped titanium-boron control component with a titanium cladding. Blades for such control rods have been successfully prepared in cooperation with the Battelle Memorial Institute by a picture-frame rolling technique. The rolling packs, which are machined from type 304 stainless steel, contain sintered titanium boron and wrought hafnium core materials in a commercially pure titanium envelope. Such packs are evacuated, sealed off, and rolled at 1600°F with a total reduction of 3/1 using 20% reduction per roll setting. Post-fabrication treatments include (1) mechanical removal of the stainless steel envelope, (2) flat annealing, (3) machining, and (4) stress relief annealing.

Data on the mechanical properties, corrosion performance, thermal cycling resistance, and irradiation damage resistance of composite control rod components are presented in this report. This information strongly indicates that composite control rods will perform satisfactorily in water-cooled reactors.

ACKNOWLEDGMENT

It is appropriate to call attention to, and express the writer's appreciation for, the efforts of those people who assisted in gathering the data appearing in this report. The BMI personnel who, under a very tight development schedule, carried out fabrication and evaluation studies and prepared samples for use at KAPL are S. J. Paprocki, D. Keller, G. Cunningham and A. K. Foulds. The KAPL personnel who contributed to the collection of performance data are D. Belouin of Coolant Chemistry, R. Siergiej of Mechanical Metallurgy and Metallography, R. P. Renzi of Irradiations Experiments, and P. R. Mertens of SAR Reactor Materials Development.

THE DEVELOPMENT OF COMPOSITE CONTROL RODS FOR WATER-COOLED POWER REACTORS

W. E. Ray

INTRODUCTION

The phrase "composite control rod" is used herein to describe a three-bladed control component consisting of (1) a titanium section connecting the rod to the driving mechanism, (2) a titanium-clad titanium 3.5 w/o B^{10} dispersion section, and (3) a titanium-clad hafnium tip. The latter two sections may be encased in a common cladding envelope and fabricated together, or may be fabricated separately and then fusion welded together later. This type of control component was conceived to avoid the extensive irradiation damage incurred by materials containing B^{10} in amounts greater than approximately one volume per cent. This damage is the result of the (n- α) reaction which decomposes B^{10} to Li^6 and He^4 with attendant large volume changes and/or stress generation.

The composite control rod design circumvents this difficulty because the B^{10} -containing section is not irradiated to more than 0.5 atom per cent burnup. Control of the reactor is accomplished using the hafnium tip of the rod. The B^{10} dispersion is used only to provide the additional negative reactivity required to shut down the reactor and is never in the core during operation.

When attempts to apply the round die hot coextrusion technique to the fabrication of composite control rods were unsuccessful, it was decided to continue the work by substituting a picture frame rolling technique since more freedom can be exercised in choosing a fabrication envelope. In particular, it was felt that the use of a harder material might permit "ironing" of the hafnium-dispersion joint which would result in a more uniform thickness of the control rod blades. The use of fillet envelope materials which have hardnesses in excess of that of mild steel greatly increases the pressure required for round die hot coextrusion. For this reason, and because stepwise "ironing" of a blade by its fabrication envelope is realized only in rolling, it was decided that a study of picture frame rolling should be undertaken at Battelle Memorial Institute.

This investigation covered two types of composite control rod blades: (A) the integrally rolled type of blade (see Figure 1) which is prepared by rolling both core materials in one rolling pack and which yields metallurgically joined hafnium and dispersion sections encased in a common cladding, and (B) the welded blade (see Figure 2) assembly which is prepared by rolling the two titanium-clad sections separately, then machining them to final dimensions and joining their titanium end closures together.

The welded composite control rod blade obviously requires twice as many precisely machined rolling packs and more mill time as the integrally rolled blade. It is estimated that welded blades would cost 30% more than the integrally rolled ones on this basis. Therefore, the integral design was chosen as a reference and the welded blade type was considered an alternate.

Since detailed information regarding the fabrication studies is reported elsewhere,⁽¹⁾ this report includes only generalities concerning that part of the work. In addition to the fabrication work, BMI performed certain tests on composite samples, the data from which provide information on probable composite control rod performance under reactor conditions. Such data are included herein, with suitable acknowledgment, to supplement KAPL test information.

PROCEDURE

The procedure used in preparing the integrally rolled composite control rod blades and the alternate rolled and welded blade assemblies appears in the flow diagram, Figure 3. Since most of the work performed involved the reference integrally rolled blades, a partially assembled rolling pack is shown in Figure 4. These packs are welded shut after assembly, then evacuated at about 300°F, and sealed off by crimping the evacuation tube.

The rolling pass sequence used in fabricating a typical full-size blade of the integrally rolled type is shown in Table I. Upon completion of this schedule, the pack is put back into the preheating furnace which is turned off and allowed to cool to about 200°C at which temperature the pack is removed. The stainless steel envelope is removed by milling its edges until titanium is contacted, then peeling off the cover plates.

The exposed blades are then bolted between two heavy, flat stainless steel plates and flat annealed for two hours at 1500°F. After the core material has been located radiographically, the beveling of one long edge and removal of excess cladding material from the other is accomplished in a shaper. Intermediate radiographs are taken to ensure that the machining operations are proceeding according to plan. After the reference cross

FIGURE 1. INTEGRALLY ROLLED COMPOSITE CONTROL ROD BLADE, SHOWING FINISH-MACHINED DIMENSIONS

(1) ADJUSTED AFTER WELDING TO GIVE BLADE LENGTH OF $\frac{32.56''}{31.94''}$

FIGURE 2. COMPONENTS OF WELDED COMPOSITE CONTROL RCD BLADE, SHOWING FINISH-MACHINED DIMENSIONS (EXCEPT OVER-ALL LENGTH)

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FIGURE 3. FABRICATION FLOW CHART FOR COMPOSITE CONTROL ROD BLADES

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sectional shape has been realized (see Figure 1), the ends of the blades are machined to final cladding thickness. A second flattening anneal completes the blade fabrication procedure.

No experience has been gained to date relative to the joining of three blades and a hub to yield a finished composite control rod. However, it is felt that the technique would approximate the one used in manufacturing hafnium control rods. (2)

In order to evaluate this type of control rod for water-cooled power reactor applications, a number of mechanical property, corrosion, thermal cycling, and static irradiation tests were performed. Since some of the

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TABLE I. Roll Pass Sequence for Composite Control Rod Processing⁽¹⁾

Rolling ⁽²⁾ Pass	Mill Setting (inches)	Theoretical Percent Reduction	Observed Springback (inches)
1	0.888	20	0.072
2	0.888	0	0.045
3	0.705	20	0.075
4	0.705	0	0.050
5	0.550	20	0.080
6	0.550	0	0.047
7	0.430	20	0.075
8	0.430	0	0.050
9	0.340	19.38	0.063
10	0.340	0	-

(1) Data obtained by BMI.

(2) Rolling pack flipped and reversed before reheating for each even-numbered pass except pass number 2.

tests are of a long-term nature, it was necessary to begin them before the control rod fabrication procedure was firmly established. For this reason the Ti-3.5 w/o B¹⁰ dispersion irradiation and static corrosion test samples were prepared by the best fabrication method known at the time - round die hot coextrusion.⁽³⁾ The extrusion temperature was 850°C, and a 4.8/1 reduction was taken. In the case of titanium-clad irradiation growth test samples, the 0.25 x 1.125 x 30-inch long as-extruded dispersion rod was cut into 5-inch lengths and closure of the ends was effected by fusion welding 0.5-inch long end plugs into place. These samples were mounted into irradiation test capsules such as the one shown in Figure 5. Observe that the sample surface is accessible to the MTR coolant water. Pre-irradiation testing of such samples was performed using adjacent sections of the extruded rod and included chemical analyses for boron content and metallographic examination. Two capsules (numbers 28-39 and 28-40) were inserted into high-flux positions in MTR to obtain irradiation growth data. Capsule 28-39 was irradiated to a calculated 0.5 atom per cent B¹⁰ burnup, which is the maximum exposure anticipated in the shutdown portion of composite control rods. Capsule 28-40 was exposed until a calculated one atom per cent B¹⁰ burnup was attained. After irradiation, the samples were removed from their capsules, sectioned for metallographic examination, and analyzed for Li⁶ to verify the B¹⁰ burnup obtained in MTR.

FIGURE 4. Stainless Steel Rolling Pack Containing Composite Control Rod Blade Assembly with Cover Plates Removed

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FIGURE 5. Irradiation Capsule Containing Composite Control Rod Test Sample to Be Irradiated in Contact with Reactor Coolant Water

KS-17496
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FIGURE 6. Apparatus Used in Performing Bend Tests on Both Irradiated and Unirradiated Materials

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The unclad dispersion samples used in obtaining bend test data were also fabricated by the referenced extrusion procedure. In this instance, the irradiation samples were prepared by machining as-extruded strip to the 0.050 x 0.200 x 3-inch size. The pre-irradiation test procedure was as described above. All bend-test samples were irradiated in NaK-filled capsules containing four samples each and designed in such a way that the irradiation temperature was approximately 450° F. After exposure to design burnup, the capsules were returned to KAPL from MTR, and dismantled. The NaK was then analyzed for purity and the samples were cleaned and visually examined. A bend test followed, using the apparatus shown in Figure 6. In this test the sample is supported at the ends and the load is applied at the middle of the span until fracture occurs or until the angle included by the sample is about 110°. By passing current through the sample, it is possible to test materials in this apparatus at elevated temperatures. The metallographic structure and actual B¹⁰ burnup of each sample is determined using the undeformed ends of bend-tested material.

Bend tests on unirradiated materials were performed by BMI using 0.25-inch thick sections from full-size control rods. These samples were all titanium-clad on the top and bottom but not on the sides. The work involved the bending of clad dispersion and hafnium samples after annealing for 0, 10, 100, 500, and 1000 hours at 680° F in argon-filled ampules. Testing was carried out in most instances at a nominal temperature of 680° F by preheating the sample in a furnace, then placing it into the bending jig and performing the test as rapidly as possible. The jig used was designed in such a way that a maximum bend (over a 0.25-inch radius) of 93° could be obtained.

To augment the bend-test information, tensile tests were performed by KAPL and BMI at room temperature and at 700° F. The samples employed were of the integrally rolled composite type shown in Figure 7. A strain rate of 0.003 inch per minute was employed until plastic deformation of the sample began. The elevated temperature test by B.M.I. was performed with an argon-filled furnace around the sample. The temperature was read from two thermocouples, the maximum indicated difference between them being 5° F.

The probable behavior of composite control rod blades in reactor coolant water was examined by means of a thermal cycling test and a static corrosion test which were both performed in deoxygenated, deionized water. The thermal cycling test was carried out under the following conditions:

Upper temperature	600° F
Lower temperature	68° F
Total time per cycle	3 min.
Number of cycles	3700

The sample used was the same as the KAPL tensile test sample of Figure 7. The static corrosion data was obtained by taking weight change data after one, two, four, and eight weeks' exposure of the sample in 680° F water. The samples used were prepared by fusion welding 1-inch long extruded⁽⁵⁾ titanium-clad hafnium and titanium-clad dispersion triflutes together. No attempt was made to exclude core materials from the welds, and the cladding and core materials were left exposed at the samples' ends. It was felt that such a sample would yield the most pessimistic corrosion rate data possible. The hafnium core material was prepared by powder metallurgy techniques, and therefore was less pure than reactor grade material.

RESULTS AND DISCUSSION

Dimensional data taken from three full-size composite control rods of the integrally rolled type are compiled in Table II. These blades had double the reference cladding thickness (see Figure 1) in the as-fabricated condition. Since these were the first blades manufactured, it was necessary to provide sufficient titanium cladding material in the pack to ensure that any reduction in over-all blade thickness at the joint between sections could be eliminated in final machining operations. These blades, shown in Figure 8, were measured in the ATR at KAPL to determine their control worth. This experiment fixed the worth of the blades at 100% $\pm$ 2% of that of 0.187-inch thick, pure reactor grade hafnium.

TABLE II

The Dimensions of Three Integrally Rolled Composite Control Rod Blades

<u>Description of Measurement</u>	<u>Maximum*</u> <u>(inches)</u>	<u>Minimum*</u> <u>(inches)</u>
Over-all outside width	3.510	3.480
Over-all outside length	34.70	34.60
Over-all outside thickness	0.259	0.255
Total poison material length	32.80	32.60
Hafnium length	15.10	14.90
Ti-3.5 w/o B ¹⁰ dispersion length	17.70	17.60
Hafnium thickness	0.215	0.187
Dispersion thickness	0.190	0.187
Thickness of cladding on beveled edge	0.360	0.330

*Maxima and minima are those found in compiling data from three blades.

Before Testing

Dispersion

Hafnium

Dispersion

Hafnium

After Testing

FIGURE 7. Integrally Rolled Composite Samples Before and After Room Temperature Tensile Testing

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FIGURE 8. Integrally Rolled Composite Control Rod Blade with Cladding Machined to Final Thickness

KS-25076

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FIGURE 9. Samples from Welded Composite Control Rod Blade Assembly

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Voids are Due to Removal of Boron Particles During Metallographic Polishing

FIGURE 10. Small Scale Composite Control Rod Blade Prepared by Rolling in a Type 304 Stainless Steel Pack at 1600°F (Reduction Ratio 3/1)

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TABLE III. Dimensions of Blade Sections Suitable for Use in Composite Control Rod Blades of the Welded Type

Description of Measurement	Blade #1		Blade #2		Blade #3	
	Hf Sect.	Ti-3.5 B ¹⁰ Sect.	Hf Sect.	Ti-3.5 B ¹⁰ Sect.	Hf Sect.	Ti-3.5 B ¹⁰ Sect.
Over-all outside length*	15.910 $\pm$ 0.002	18.190 $\pm$ 0.002	15.840 $\pm$ 0.002	18.530 $\pm$ 0.002	15.880	18.350 $\pm$ 0.002
Over-all outside width	3.521 $\pm$ 0.001	3.514 $\pm$ 0.001	3.521 $\pm$ 0.001	3.519 $\pm$ 0.001	3.522	3.518 $\pm$ 0.001
Over-all outside thickness	0.256 $\pm$ 0.003	0.250 $\pm$ 0.002	0.255 $\pm$ 0.004	0.250 $\pm$ 0.002	0.256 $\pm$ 0.003	0.250 $\pm$ 0.002
Ccre material length	14.880 $\pm$ 0.010	17.140 $\pm$ 0.010	14.770 $\pm$ 0.010	17.180 $\pm$ 0.010	14.820 $\pm$ 0.010	17.050 $\pm$ 0.010
Ccre material width	3.092 $\pm$ 0.008	3.140 $\pm$ 0.020	3.085 $\pm$ 0.005	3.130 $\pm$ 0.020	3.085 $\pm$ 0.005	3.135 $\pm$ 0.015
Flat edge clad thickness	0.030 $\pm$ 0.010	0.035 $\pm$ 0.005	0.035 $\pm$ 0.015	0.035 $\pm$ 0.005	0.025 $\pm$ 0.015	0.040 $\pm$ 0.010
Bevel edge clad thickness	0.395 $\pm$ 0.005	0.335 $\pm$ 0.015	0.397 $\pm$ 0.008	0.340 $\pm$ 0.010	0.420 $\pm$ 0.015	0.345 $\pm$ 0.005
Blade faces clad thickness	0.033 $\pm$ 0.002	0.035 $\pm$ 0.002	0.035 $\pm$ 0.002	0.035 $\pm$ 0.002	0.035 $\pm$ 0.002	0.035 $\pm$ 0.002

* Includes 1.000 inch $\pm$ 0.003 inch of end closure titanium on each end.

In addition to these three integrally rolled blades, three hafnium and three dispersion plates clad with titanium were manufactured for use in assembling three alternate welded composite blades. Since the work with integrally rolled composite blades had established the pre-rolling blade dimensions, these were rolled to finished cladding and over-all thickness. The finished dimensions of the six finished blade sections appear in Table III. The extra length of titanium on the ends of the sections would be used as follows in preparing a finished control rod (see Figure 10):

Hub end of dispersion	90° bevel for weld to hub
End of dispersion adjacent to Hf section	90° bevel for weld to Hf section
End of Hf adjacent to dispersion section	90° bevel for weld to dispersion section
Free end of Hf section	Leave as is until longitudinal welds are made, then face back to 0.015-inch minimum thickness

The design for the 90° bevel weld joint was tentatively established by welding trials at KAPL. In this work, 2.5-inch wide samples were joined using four filler weld passes under the following conditions (no welding chamber was employed):

Voltage	10 d-c
Amperage	84
Polarity	Straight
Torch travel	1 inch per minute (approx.)
Gas shielding	19 cfh argon through No. 12 nozzle

The 75A titanium filler material was hand-fed into the bead as required.

The variable investigated was the distance from the shoulder to the edge of the 90° bevel. The results obtained indicate that a 0.185-inch distance, giving a total joint length of about 0.38 inch, can be used (see Figure 9) without modification of the metallographic structure of the bond layers in the two sections joined. Smaller separation distances tend to produce voids in the bond between the hafnium and its titanium cladding.

The metallographic structure of the hafnium-containing diffusion bonds formed during the rolling procedure was investigated by BML (3). The general nature of such bonds is shown in Figure 10. Note that (1) the layers are of very uniform thickness, and (2) that no diffusion appears to have occurred between hafnium and B¹⁰ particles contacting it. The fact that hafnium-titanium diffusion bonds scavenge hydrogen from adjacent titanium areas is shown in Figure 11, sample "A". The samples shown in Figure 11 were given additional cold reduction after being fabricated by the picture frame rolling technique already

Cold Reduced 20%
250X (Sample A)

Reduced 50% 650°F
250X (Sample B)

(Note that Hydrides have been Formed in Bond Layer)

FIGURE 11. Titanium-Clad Hafnium Rolled in Stainless Steel Pack at 1600°F to 3/1 Reduction (Small Scale)

KS-25077

Unclassified

FIGURE 12. Hafnium-Titanium Bond Made by Hot Rolling at 1600°F in Stainless Steel Pack. Structure Near Outside Radius of 80 Degree Bend Made at Room Temperature. 250X

KS-25078

Unclassified

100X

Near Penetration into Clad

100X

Near End of Crack in Titanium-B Section

FIGURE 13. 3.5 W/O Borax in Titanium, Titanium-Clad Prepared by Hot Rolling at 1600°F in Stainless Steel Pack - 20 Degree Bend at 650°F

KS-25079

Unclassified

(A) Titanium Clad, Titanium
3.5 Weight % B Dispersion (2X)

(B) Titanium-Clad Hafnium (2X)

FIGURE 14. Exposed Ends of a Composite Control Rod Sample after Autoclaving for 1000 Hours in Degassed, Deionized Water at 680°F

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presented, then sample "B" was heated to 1500° F and water quenched. This was done to (1) examine the resistance of the hafnium-titanium diffusion bond to cold deformation and thermal shock, and (2) to examine the possibility of cold finishing composite blades. Since no failures were produced in the bonding layer, it appears that the bond has enough ductility to resist drastic thermal shock and to permit cold finishing of composite control rod blades if desired. Note that the sample "B" of Figure 11 shows that the heavy concentration of hydrides in the bond layer is somewhat reduced by the final anneal called for in Figure 3. This anneal apparently beta-transforms the Ti-Hf alloy bond layer.

The mechanical properties of the diffusion bond joining the hafnium to its titanium cladding have not been fully established. However, reference to the bend-test data of Table IV will show that the ductility of this layer is adequate and is not seriously impaired by long-term holding at ordinary reactor coolant water temperature. The metallographic structure of this hafnium-titanium alloy bond on the tensile side of a sample bent 80° at room temperature appears in Figure 12. Note that no cracks have appeared even though the bond layer is heavily contaminated with hydrides. A failure produced in a natural boron dispersion sample (number 1 in Table IV) is shown in Figure 13. This failure was apparently produced because of the large percentage of fines in the normal boron stock used. The crack apparently initiated at a boron particle about 0.050 inch on the tensile side of the neutral axis of the sample. It propagated between boron particles and did not produce lateral failure along the clad-to-core interface. It is felt that this bend-test data strongly indicates that the composite control rod has sufficient ductility for use in water-cooled, water-moderated power reactors.

Tensile stresses may be applied to control rods in service by (1) stopping the rod after a rapid shutdown and (2) by attempting to withdraw a rod which is lodged in its channel. In order to withstand these applied stresses, it is estimated that control rod materials should have 0.2 offset yield strengths of at least 7,000 psi both at room temperature and at 680° F. The data in Table V shows that the integrally rolled composite control rod will easily meet this requirement. Figure 7 is a photograph of a tested and an untested KAPL tensile sample. Note that failure occurred in the dispersion material about one eighth of an inch from the jointure. This behavior was typical of all three tests.

The resistance of the jointure between the dispersion and hafnium sections to stresses imposed by thermal cycling between 600° F and room temperature in water was examined in a test already described. The dimensions of the sample before and after testing are listed in Table VI, the indicated changes being within the error of measurement. The only change in the

TABLE IV

Bend Test Data Obtained(*) Using Titanium-clad Sections from Full-size Integrally Rolled Composite Plates

<u>Sample Number</u>	<u>Core Material</u>	<u>Post-Fabrication Heat Treatment(**)</u>	<u>Bend Test Temperature</u>	<u>Degrees Bend over 0.875-inch Radius(†)</u>	<u>Observation</u>
1	Ti-3.5 weight % B ⁿ	None	Room	18	Failed
2	Ti-3.5 weight % B ¹⁰	None	680° F	90	No failure
3	same	10 hours at 680° F	680° F	52	No failure
4	same	100 hours at 680° F	680° F	90	No failure
5	same	500 hours at 680° F	680° F	90	No failure
6	same	1000 hours at 680° F	680° F	90	No failure
7	Hf	None	Room	82	No failure
8	Hf	None	680° F	93	No failure
9	Hf	10 hours at 680° F	680° F	93	No failure
10	Hf	100 hours at 680° F	680° F	93	No failure
11	Hf	500 hours at 680° F	680° F	93	No failure
12	Hf	1000 hours at 680° F	680° F	90	Small cracks produced

(*) Obtained by BMI

(**) In argon-filled capsules

(†) Maximum bend attainable was 93°

TABLE V

Tensile Test Data from Samples Machined from Full-size Integrally Rolled Composite Blades

Sample Type	Test Temperature	0.2% Offset	Ultimate Tensile Strength, (psi)	% Elong. in 2 inches	% Red. in Area	
		Yield Strength, (psi)			Hf Section	Disp. Section
See Figure 7	Room	69,800	44,300	12.5	16.6	8.0
See Figure 7	Room	68,400	44,900	7.9	12.9	3.9
Standard with clad on flat faces only; Hf dispersion joint at center*	700° F	13,000	19,700	13.2	-	-
Same*	700° F	13,500	19,600	11.2	-	-

*Tested by BMI

samples' appearance produced by cycling was a very thin, tightly adherent bluish film of corrosion product.

TABLE VI

Pre- and Post-testing Dimensions of a Composite Sample Thermally Cycled 3700 Times between 68° and 600° F in Water

<u>Position of Measurement</u>	<u>Dimension (inches)</u>	
	<u>Pre-cycling</u>	<u>Post-cycling</u>
Hf end closure, width	1.179	1.178
Hf-to-dispersion joint, width	1.177	1.176
Dispersion end closure, width	1.179	1.179
Hf end closure, thickness	0.261	0.260
Middle of Hf section, thickness	0.252	0.252
Hf-dispersion joint, thickness	0.268	0.268
Middle of dispersion, thickness	0.247	0.246
Dispersion end closure, thickness	0.250	0.248

The corrosion behavior of titanium in high-temperature water has been widely studied and the corrosion rates reported are very low. Since the proposed composite control rod is completely encased in commercially pure titanium, the only data required to establish the feasibility of this rod from a corrosion standpoint are the rates of attack which might be encountered in a ruptured rod. Preliminary data on plates of Ti-3.8 w/o B¹⁰ and Hf which were bolted together have been reported by WAPD. This information indicates that the dispersion will lose about 320 mg/dm² in 90 days, beginning at an initially high rate which changes to a rate of approximately 42 mg/dm²/month after about 25 days. The rate of hafnium corrosion was negligible, KAPL data, from samples which included a Hf-Ti couple, a titanium-dispersion couple, and a titanium weld contaminated with both boron and hafnium appear in Table VII.

The appearance of the dispersion end of the sample which was pickled before autoclave exposure is shown in Figure 14. The white corrosion product (which is probably hydrated B₂O₃) can be seen. With this exception, the appearance of the sample was unchanged by the test. Since the KAPL test more closely simulates a composite control rod with ruptured cladding, it is considered that the corrosion performance of this type control component is adequate. If the cladding were completely removed, the WAPD data would be more appropriate, but it is extremely unlikely that this situation will occur.

Etched (100X)

Etched (250X)

FIGURE 15. Photomicrographs of Titanium-Clad, Titanium-3.5 W/O.Boron¹⁰ Dispersion Material Irradiated in Capsule 28-29

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FIGURE 16. Portion of Irradiated Titanium-Clad, Titanium-3.5 W/O Boron Dispersion Near Welded End Closure

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TABLE VII

Weight Change Data on Titanium-clad Hafnium and Ti-3.5 w/o B¹⁰ Dispersions
Joined by Welding* and Corroded in 680° F Degassed, Deionized Water

Surface Conditioning	Weight Change (mg/dm ²) ²			
	168 hours	336 hours	1000 hours	2000 hours
Degreased only	+42.3	+55.9	+87.0	+123.0
Degreased and acid pickled	- 1.22	- 0.35	+ 0.70	+ 1.57

*Both core materials exposed at sample ends.

Unfortunately, it became necessary to terminate this program before irradiation capsules containing integrally rolled composite plates (such as the one shown in Figure 7) could be irradiated in MTR. However, a significant body of information on the irradiation performance of the dispersion, which is the core material more prone to irradiation damage, has been gathered. Data on the growth of two 0.250 x 1.125 x 6-inch samples of Ti-3.5 weight % B¹⁰ clad with 0.025 inch of titanium appear in Table VIII. Sample 28-39 was irradiated to a calculated 0.5 atom per cent burnup of the B¹⁰ atoms present, whereas sample 28-40 sustained a calculated 1.0 atom per cent burnup. The dimensional changes shown in Table VIII for capsule 28-39 are within the error of measurement, which implies that no shear stresses would be applied to the dispersion-hafnium joint in an integrally rolled blade as a result of irradiation damage. Two typical photomicrographs from sample 29-39 are shown in Figure 15. It can be seen that irradiation effects on the B¹⁰ particles were not significant. The photomicrograph of Figure 16 shows an area of the cladding-core bond of sample 28-40 which was close enough to the weld to have a beta-transformed cladding structure. Since this area is also undamaged, suitable irradiation performance of welded joints in rods using integrally rolled blades and in those employing the alternate welded blade assembly is implied. The adequate irradiation performance of hafnium to titanium welds has reportedly been established by Westinghouse (Bettis Site).

Data on the post-irradiation performance of the dispersion under mechanical stresses is fragmentary in that data at the operating temperature of the rod are entirely lacking. Results obtained by bending seven irradiated coupon samples (200 x 50 x 3 inches) at room temperature appear in Table IX. It seems apparent that no serious loss in ductility results from irradiating this dispersion to double the burnup expected in the shutdown portion of composite control rods.

TABLE VIII

Irradiation-induced Growth of Ti-3.5 Weight Percent B¹⁰ Dispersion Plates

Capsule Number	Sample Number	Dimensions	Clad Thick.	A/o B ¹⁰ B. U.	Avg. Percent Growth		
					Length	Width	Thickness
28-35	1*	0.050x0.200x3.00	None	5.48	0.30	1.90	4.50
	2*	same	None	5.48	0.30	0.44	6.40
	3*	same	None	5.48	0.25	2.20	5.20
	4**	same	None	5.48	0.25	1.90	4.10
28-39	1	0.250x1.125x6.00	0.030	-	-	-	+0.23
28-40	2	same	0.030	-	-	+0.30	+0.16
28-55	1	0.050x0.200x3.00	None	0.80	(/)	0.1	0.6
	2	same	None	0.80	-	0.3	0.7
	3	same	None	0.80	-	0.2	1.7
	4	same	None	0.80	-	0.4	1.3
28-56	1	same	None	1.48	(/)	0.4	1.7
	2	same	None	1.48	-	0.7	1.1
	3	same	None	1.48	-	0.5	1.3
	4	same	None	1.48	-	0.6	1.3

* Surface warts associated with B¹⁰ particles, no cracking apparent at 4X.

** Surface warts associated with B¹⁰ particles, incipient cracks noted.

(/) Unavailable

TABLE IX. Bend Test Data from Irradiated Ti-3.5 Weight Percent B¹⁰ Dispersions of Table VIII

Capsule Number	Atom % B ¹⁰ B.U.	Max. Load, (pounds)	Deflection at Max. Load (inches)	Deflection at Fracture (inches)
28-35*,**	0	22	0.300	No fracture
28-35**	5.48	30	0.170	0.170
28-35**	5.48	30	0.200	0.200
28-55	0.80	31	0.390	0.390
28-55	0.80	32	0.230	0.230
28-56	1.48	32	0.275	0.275
28-56	1.48	33	0.370	0.370

* Unirradiated control sample

** Samples showed extensive local swelling near B¹⁰ particles

SUMMARY AND CONCLUSIONS

The fabrication of Ti-3.5 w/o B¹⁰ dispersion control rods with hafnium tips which are entirely clad in titanium has been reduced to practice by BMI under KAPL cognizance. The picture frame rolling technique is employed with reductions of 3/1 at 1500° F being taken on the stainless steel-clad pack. Testing of the finished plates has yielded satisfactory data on mechanical properties, dimensional control, and metallurgical stability.

Corrosion and irradiation performance testing has emphasized the Ti-3.5 w/o B¹⁰ dispersion since the performance of this material is considered limiting from both these standpoints. The corrosion performance information on both the dispersion and titanium-clad hafnium are considered satisfactory since the dispersion portion of the rod (which had inadequate corrosion resistance) will be titanium clad. The irradiation stability of the dispersion is adequate at the 0.5 to 0.75 a/o burnup anticipated for the shut-down (upper) section of the composite control rod. Growths at these exposures were below 1.75 percent in thickness and below 0.5 percent in width for 0.200 x 0.050-inch platlets without cladding.

Assembly of the composite plates with a hub to yield a finished control rod has not yet been reduced to practice. Preliminary fusion welding tests on sub-scale samples are promising. It is therefore concluded that this rod shows promise for application in water-cooled nuclear reactor cores.

RECOMMENDATIONS

To fully demonstrate the suitability of the composite control rod for reactor service, the following additional information is required:

(1) The post-irradiation tensile properties and corrosion performance of the Hf (Ti-3.5 w/o B¹⁰) dispersion joint.

(2) The creep strength of the above joint and of the dispersion after irradiation to 0.8 a/o of the dispersion.

(3) The irradiation performance of a composite, titanium-clad sample in water at 500° to 600° F.

(4) The assembly of composite blades into a finished control rod must be reduced to practice.

It is recommended that these data be obtained on a low-priority basis as a part of the over-all effort to device control rods which conserve reactor grade hafnium.

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