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IRRADIATION EFFECTS ON BORON-CONTAINING CERAMICS AND CERMETS

J. G. Morgan
P. E. Reagan
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IRRADIATION EFFECTS ON BORON-CONTAINING CERAMICS AND CERMETS

J. G. Morgan
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M. T. Morgan

DATE ISSUED

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IRRADIATION EFFECTS ON BORON-CONTAINING CERAMICS AND CERMETS

J. G. Morgan P. E. Reagan M. T. Morgan

ABSTRACT

Studies of irradiation effects are presented on two ceramics, B_4C and BN, and three stainless-steel-clad cermets, BN–Ni, CaB_6–Fe, and Cu–B_4C, which contained natural boron. The B_4C retained dimensional stability at 1% average B^{10} burnup at temperatures up to 815°F. Property changes and gas evolution were measured on irradiated BN, both hot-pressed and as a powder. Stainless-clad BN–Ni and CaB_6–Fe showed damage at burnups of 38% for low-temperature irradiations. The Cu–B_4C material showed damage above 420°C at 18% average B^{10} burnup. The damage was thought to be primarily due to the thermal history of the Cu–B_4C specimens.

INTRODUCTION

Neutron shield materials containing boron have a high potential for radiation damage because of the (n,α) reaction. In effect, this amounts to a fission of the boron atom into an atom of helium and an atom of lithium. In other shield materials, where the (n,α) reaction is not present, the rate of damage is much less and originates from energetic gamma recoils.

The most important advantage of using a boron-containing material is the low secondary-gamma level at the outside of the reactor shield, especially important in mobile reactors. Boron is easily fabricated as metal dispersions, alloys, or ceramics and has a high neutron cross section that extends into the epithermal region (Fig. 1). Studies of radiation effects were made on two types of boron-containing shielding materials, ceramics and cermets.

BORON CARBIDE

The most familiar boron refractory for neutron shield application is boron carbide. Irradiation effects have been studied on both single crystals[1] and bulk samples of this material. Physical stability and helium release up to 36% burnup had previously been made in a very thorough investigation at KAPL.[2]

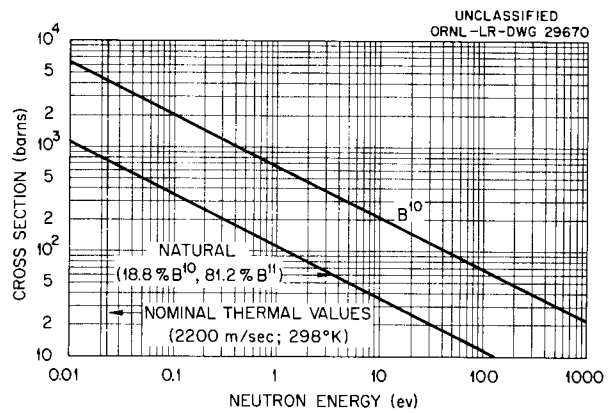

Fig. 1. Neutron Absorption Cross Sections of Natural Boron and Boron-10.

The purpose of our investigation was to screen a number of samples of various densities and purities submitted by two manufacturers. The material, in the form of tiles 3 × 3 × ¼ in., was to be used as a neutron shielding curtain surrounding the reflector of a molten-salt reactor. Irradiation times were chosen so as to achieve a maximum burnup of B^{10} atoms the same as, or greater than, that which would be produced in the molten-salt reactor. Because the geometrical conditions of irradiation are different in the LITR and the proposed molten-salt reactor, it was not possible to duplicate both the maximum burnup and the average burnup. Maximum burnup, which occurs near the surface, was considered to be the more significant quantity to duplicate in these sample irradiations. In determining an average B^{10} burnup value, two methods were used and found to be comparable.

[1] C. W. Tucker and P. Senio, *Acta Cryst.* 8, 371 (1955).

[2] W. D. Valovage, *Effect of Irradiation on Hot-Pressed Boron Carbide*, KAPL-1403 (Nov. 15, 1955).

[redacted]

In one, the incident neutron current was determined by activation of a cobalt foil positioned flat against one of the faces of the sample. From this the total number of neutrons absorbed by the sample was calculated. The other method was a measurement of the B^{10}/B^{11} ratio of the material before and after irradiation. An average value of 1% B^{10} burnup was obtained by these methods.

Fabrication data on the boron carbide samples are given in Table 1.

Table 1. Fabrication Data on B_4C Bodies

Sample A-N
Hot-pressed and sintered
High density
Boron analysis, 65.9 wt %
Hard and impervious
Sample B-N
Hot-pressed and fired at above 2000°C
Fabricated from high-purity boron carbide, 325 mesh and finer
Boron analysis, 71.8 wt %
Hard, strong, and impervious
Sample C-N
Hot-pressed and fired at above 2000°C
Fabricated from technical grade boron carbide, 60 mesh and finer
Boron analysis, 62.4 wt %
Hard, strong, and nearly impervious
Sample A-C
Cast and sintered and then bonded with SiC
Porous and friable
Sample B-C
Cast, then fired at 1350°C and refired at 2000°C
Fabricated from basic mixture of 90% B_4C grain and 10% 20-mesh silicon metal
Porous and friable
Boron analysis, 64.7 wt %
Sample C-C
Cast, then fired at 1350°C and refired at 2000°C
Fabricated from basic mixture of 80% B_4C, 10% 200-mesh and finer silicon metal powder
Porous ond friable
Boron analysis, 67.8 wt %
Sample J
Hot-pressed, high density
Boron analysis, 77.8 wt %
Hard and impervious, similar to A-N

Results. – Twenty-six samples, each $\frac{1}{4} \times \frac{1}{4} \times \frac{1}{2}$ in., were irradiated in the LITR. The samples were sealed in helium in quartz ampoules which were cooled by the reactor water (Fig. 2). The materials varied in density from 2.02 g/cc to 2.49 g/cc and in boron (natural) composition from 62.4 wt % to 77.8 wt %. The "dash C" specimens contained more trace impurities (Table 2) and were porous and friable. After irradiation the ampoules were broken and the gas release was measured (Figs. 3 and 4). Because of the low precision of this measurement (±0.1 cc), it served to measure any gross gassing which might occur as the result of fabrication methods, rather than helium evolution. One material (A-C) evolved gas, as a result of irradiation, which resulted in a coating on the inside of the ampoule (Fig. 5). This condition could not be duplicated as a result of temperature alone in a separate test out of pile. X-ray examination of irradiated specimen A-C showed an increase in disordering, with the subsequent appearance of a lessening of the degree of x-ray crystallinity. All the samples were dimensionally stable (Fig. 6), although the "dash C" specimens were too porous and friable to allow precise density or dimension measurements (Table 3).

On the basis of these studies, the tile for the neutron curtain was specified, and prototype tile samples were tested. Two irradiations, one at reactor cooling water temperature and the other at 1500°F, were made in helium on the prototype (series J) material. These samples were found to be dimensionally stable.

BORON NITRIDE

Although boron nitride was prepared for the first time in 1842, it is only recently that high-purity hot-pressed material has become readily available. Pure boron nitride is a bulky white powder with a crystalline structure similar to that of graphite. The hot-pressed material is resistant to oxidation at 1300°F and is easily machined. Directionalism is present in physical properties, especially thermal expansion.[3] Tests were conducted primarily to explore the general integrity of this relatively new ceramic, and specifically to determine irradiation effects on weight, density, and dimensions. High-purity boron nitride powder was

[3] K. M. Taylor, *Ind. Eng. Chem.* 47, 2506 (1955).

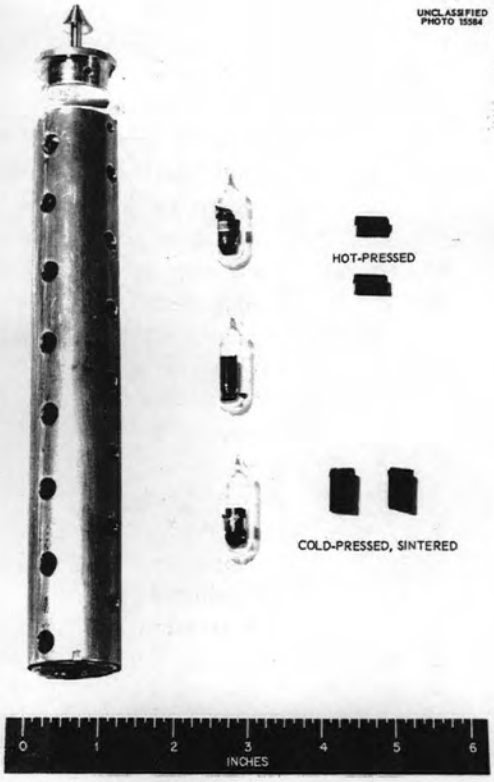

Fig. 2. Boron Carbide Specimens and Irradiation Assembly.

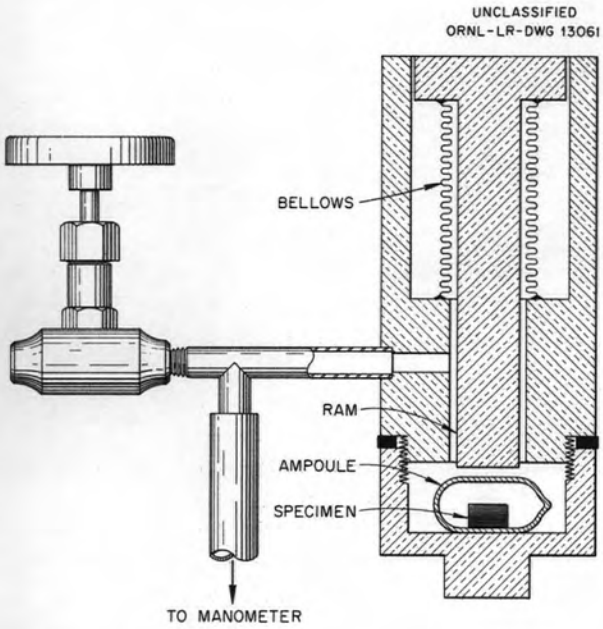

Fig. 3. Gas-Release Apparatus: Ampoule Opener.

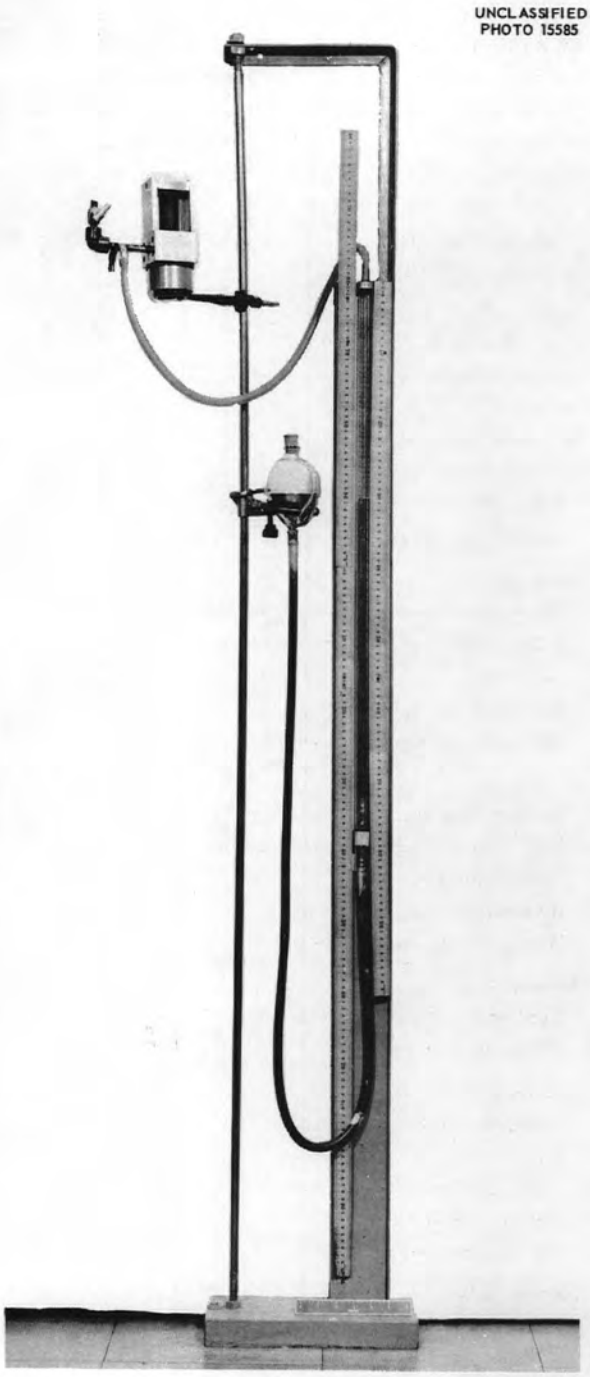

Fig. 4. Gas-Release Apparatus.

Table 2. Spectrographic Analysis of B_4C Samples

Element	Limit of Detection (%)	Amount of Impurity (%)						
		Sample A-N	Sample B-N	Sample C-N	Sample A-C	Sample B-C	Sample C-C	Sample J
Al		0.01–0.1	1–10	0.1–1	0.1–1	0.1–1	0.1–1	0.01–0.1
Ca		0.001–0.01	0.01–0.1	0.001–0.01	0.001–0.01	0.001–0.01	0.001–0.01	0.0001–0.001
Cr	0.004	*	*	*	0.01–0.1	0.01–0.1	0.01–0.1	*
Cu	0.0001	*	0.01–0.1	*	*	*	*	0.0001–0.001
Fe		0.01–0.1	0.1–1	0.1–1	1–10	0.1–1	1–10	0.01–0.1
Mg		0.0001–0.001	0.001–0.01	0.0001–0.001	0.001–0.01	0.001–0.01	0.001–0.01	0.0001–0.001
Mn	0.001	*	0.01–0.1	*	0.01–0.1	0.01–0.1	0.01–0.1	0.001–0.01
Ni	0.02	*	*	*	0.1–1	0.01–0.1	0.01–0.1	0.001–0.01
Ti	0.04	*	0.1–1	0.1–1	0.1–1	0.1–1	0.1–1	*
Zr	0.03	*	0.1–1	0.1–1	1–10	1–10	1–10	*

*Sought but not found.

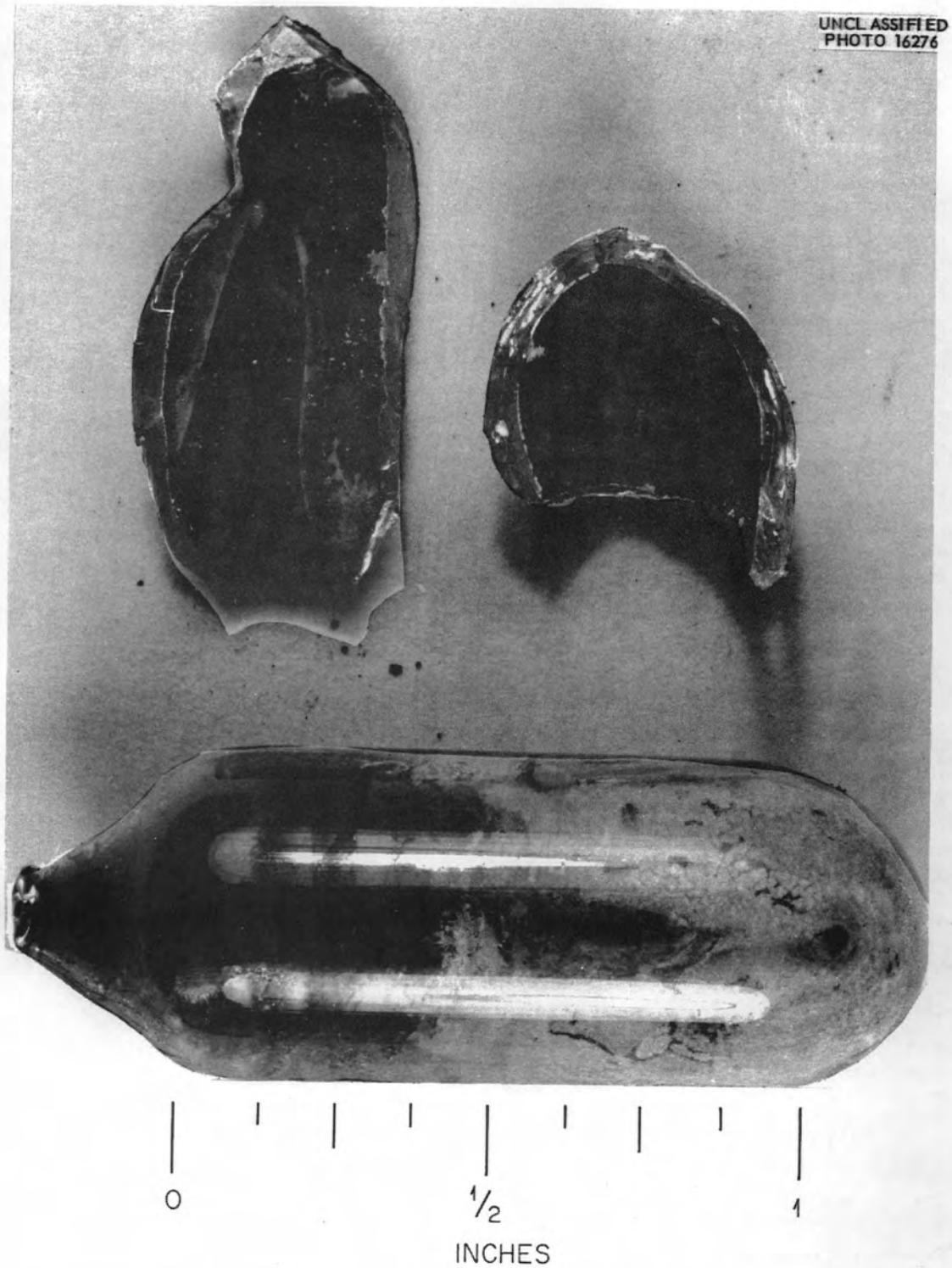

Fig. 5. Coating Inside Ampoule in Which a Cold-Pressed, Sintered B_4C Sample Had Been Irradiated. (Confidential with caption)

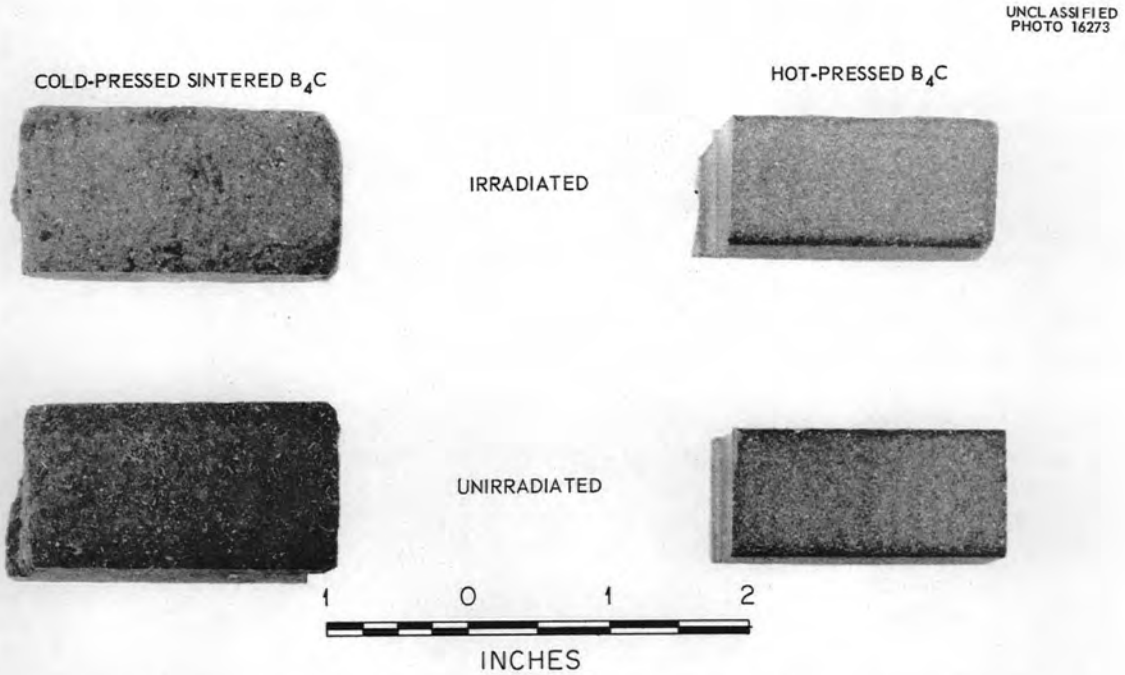

Fig. 6. Comparison of Irradiated and Unirradiated B_4C. 3X. (Confidential with caption).

Table 3. Results of Irradiating Boron Carbide Samples in the LITR

Sample	Number of Specimens	Density (g/cc)	Average Dosage, *nvt* (thermal neutrons/cm^2)	Gas Evolution	Density Change (g/cc)	Dimensional Change (in./in.)
A-N	3	2.49	6×10^{19}	0 ± 0.1 cc	0 ± 0.01	0 ± 0.001
B-N	3	2.17	6×10^{19}	0 ± 0.1 cc	0 ± 0.05	0 ± 0.001
C-N	3	2.02[a]	6×10^{19}	0 ± 0.1 cc	0 ± 0.1	0 ± 0.001
A-C[b]	3	2.1	6×10^{19}	8.1 cc/g (av)	*c*	*c*
B-C	6	*c*	6×10^{19}	0 ± 0.1 cc	*c*	*c*
C-C	6	*c*	6×10^{19}	0 ± 0.1 cc	*c*	*c*
J-1	1	2.46	3×10^{19}	*d*	0 ± 0.05	0 ± 0.001
J-3[e]	1	2.46	5×10^{19}	*d*	0 ± 0.01	0 ± 0.001

[a]Bulk density; sample slightly porous.
[b]Black deposit on container having same spectrographic analysis as sample.
[c]Samples too porous and friable to allow precise density or dimensional measurements.
[d]Not measured.
[e]Sample irradiated at 1500°F.

obtained from two manufacturers. The 6000 series material contained 42.8 ± 0.4 wt % boron with trace amounts (0.001–0.01%) of calcium, magnesium, and silicon. The C1 series material contained 43.1 ± 0.7 wt % boron with trace amounts of calcium, iron, magnesium, and silicon. Rods were pressed from these powders at 2500 psi and 2175°C for 10 min. These samples, ⅛ in. in diameter and 1½ in. long, had an average density of 2.25 g/cc.

The irradiation history and property changes are listed in Table 4. Dimensional changes were small in these tests. The changes that were detected could not be definitely attributed to radiation effects because the material is soft and easily scraped. The Mohs' scale hardness of 2 before irradiation increased to 2.5 after irradiation. Figure 7 shows a boron nitride sample before and after a high-temperature irradiation. The irradiated sample had a black surface coloration due to metal deposited from the hot walls of the container. All high-temperature irradiations were in helium, and the low-temperature tests were in a vacuum. The low-temperature tests resulted in a pale bluish-gray coloration of the sample, thought to be due to irradiation. Table 5 is a typical result of the x-ray diffraction study on this material, which showed an expansion in the *c* axis of 1.6%.

Gas Evolution. – Because the (n,α) reaction with $B^{10}N$ produces helium, leaving free nitrogen, the evolution of these gases was studied on the powder and pressed bodies irradiated at reactor water temperature under a vacuum. An apparatus for vapor-phase chromatographic analysis was made with a silica gel adsorption column and argon as the carrier gas.

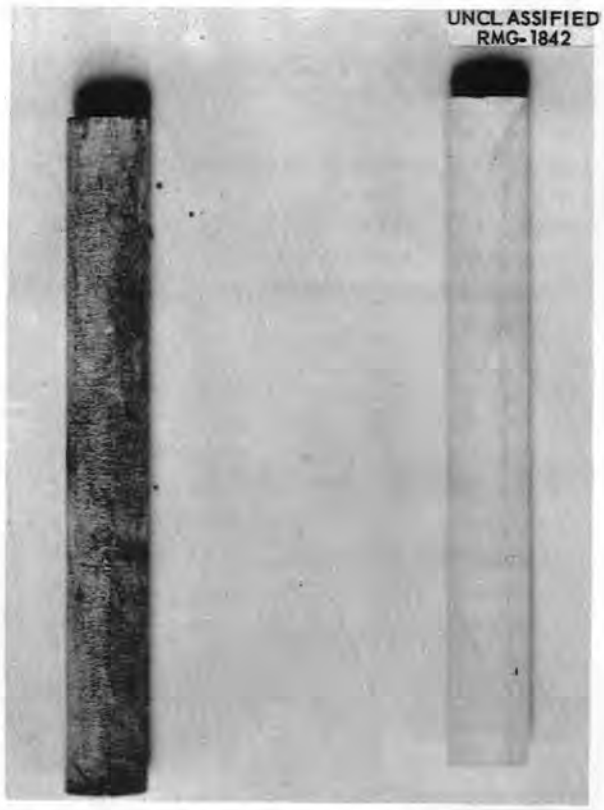

Fig. 7. Hot-Pressed Boron Nitride, Unirradiated and (Darker Sample) Irradiated at 1780°F to 4% Average B^{10} Burnup. (Confidential with caption)

Table 4. Irradiation History of Hot-Pressed Boron Nitride

Sample Number	Test Facility	Temperature (°F)	Time (hr)	Dosage (thermal neutrons/cm^2)	Weight Change (%)	Density Change (%)	Dimensional Change (%)	Average B^{10} Burnup (%)
6002-1	MTR, A-28	1600	710	1.3×10^{20}	0.9	None	None	6.0
6002-2	LITR, C-39	70	1674	1.02×10^{20}	−1	−1.3	0.4	4.8
6002-3	LITR, C-39	70	1675	1.02×10^{20}	−0.8	−2.3	1.2	4.8
6002-4	MTR, A-28	1780	606	8.72×10^{19}	*	0.13	0.1	4.0
6002-8	Bench test	1470	600	None	0.26	0.77	None	
C1-11	LITR, C-39	70	1148	7.02×10^{19}	None	None	−1.2	3.8
C1-12	LITR, C-39	70	1148	7.02×10^{19}	None	0.5	−1.2	3.8

*Not measured because of loss of chips when sample was broken.

Table 6 gives the results obtained by this analysis. The material liberated a large fraction of the helium formed, but the hot-pressed body appeared to retain the nitrogen.

BORON DISPERSIONS

Two dispersion-type materials developed by the Metallurgy Division were tested for radiation stability. Both materials contained natural boron and were clad with stainless steel for compatibility with adjacent metals in the neutron curtain. The fabrication history follows.[4]

[4] J. H. Coobs, private communication.

1. The powders were mixed 2 hr in an offset rotary blender.

2. The mixed powders were cold-pressed at 33 tons per sq in. in a $2 \times 2\frac{1}{4}$-in. steel die.

3. The cold-pressed compacts were sintered 1 hr at 2000°F in a hydrogen atmosphere.

4. The sintered compacts were coined at 33 tons per sq in. to 0.250 in. thickness in a $2 \times 2\frac{1}{4}$-in. steel die.

5. The cermet cores were encapsulated in type 304 stainless steel picture frames.

6. The picture frames were hot-rolled at 2000°F to a total reduction in thickness of 7:1.

7 The specimens were machined from the rolled composite sheet (specimen size, $0.1875 \times 0.500 \times 0.050$ in.).

The particle size of the powders and the composition of the cermet core materials are given in Table 7.

Table 5. X-Ray Diffraction Results on Irradiated Boron Nitride

Index	Interplanar Spacing (Å)		
	Original Powder	Unirradiated Hot-Pressed Samples*	Irradiated Sample 6002-1**
002	3.32	3.33	3.37
100	2.17	2.17	2.17
101		2.06	2.06
102	1.81	1.82	1.82
004		1.66	1.68
104		1.32	
110		1.25	1.25
112		1.17	1.17

*Hexagonal, $a = 2.50$ Å, $c = 6.64$ Å.
**Hexagonal, $a = 2.50$ Å, $c = 6.74$ Å. The expansion in c is 1.6%.

Table 7. Particle Sizes and Compositions of Cermet Shield Materials

Cermet	Component	Particle Size (μ)	Weight of Component (%)	Volume of Component (%)
CaB_6–Fe	CaB_6	44 to 100	7.6	21.0
	Fe	147	92.4	79.0
BN–Ni	BN	10	10.3	30
	Ni	10	89.7	70

Table 6. Evolution of Gas by Boron Nitride as the Result of Irradiation

Sample	Gas Produced by Irradiation[a] (cc)		Gas Released from the Sample (cc)	
	He	N_2	He	N_2[b]
6002-16 (powder)[c]	3.2	1.6	2.1	1.8
C1-18 (powder)	6.3	3.2	5.6	0.9
C1-19 (powder)	6.3	3.2	4.6	1.4
C1-11 (hot-pressed)	3.5	1.8	1.6	<0.2
C1-12 (hot-pressed)	3.5	1.8	2.19	<0.2

[a] Calculated from B^{10} burnup.
[b] No distinction could be made in this analysis between N_2 and O_2.
[c] Average particle size $\sim 2\ \mu$. Appeared reddish gray after irradiation.

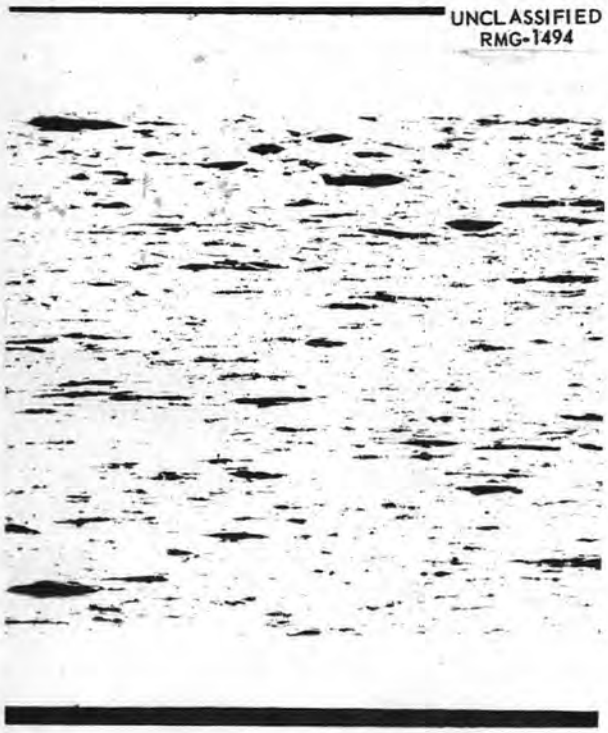

Fig. 8. BN–Ni Cermet Clad with Type 304 Stainless Steel. Unirradiated. 75X.

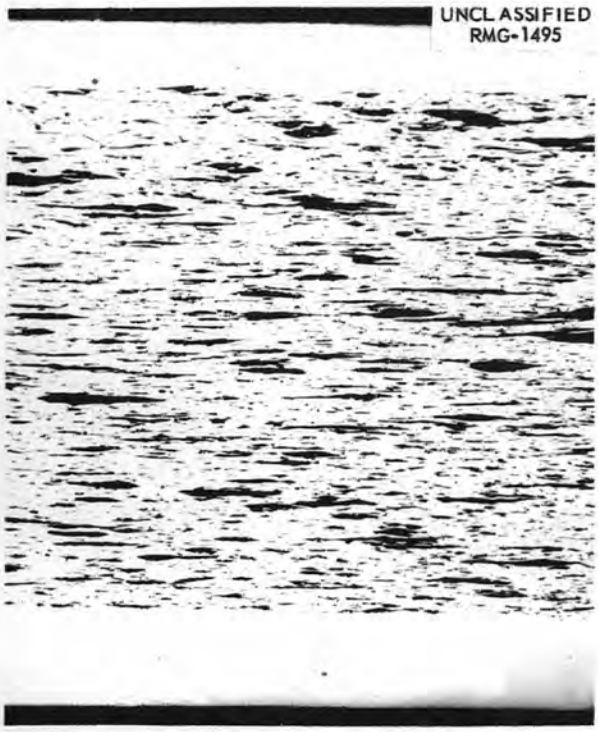

Fig. 9. BN–Ni Cermet Clad with Type 304 Stainless Steel. Irradiated to average B^{10} burnup of 19%. 75X. (Confidential with caption)

Boron Nitride–Nickel

Plates of the clad BN–Ni material were irradiated at temperatures below 345°F in evacuated quartz ampoules cooled by the LITR reactor water and were examined after two different burnups. There were no structural changes as a result of irradiation to an average B^{10} burnup of 19% but marked changes were observed at 38% burnup (Figs. 8–10). At 38% burnup the matrix was severely cracked with some separation of the cladding from the core.[5] Longitudinal splitting is shown in Fig. 11. The dimension and hardness changes are given in Table 8.

Calcium Boride–Iron

Plates of clad CaB_6–Fe material were irradiated in the same manner as the BN–Ni. The as-received material was rather inhomogeneous, and there were zones containing Fe_2B as well as a

[5]Metallographic studies were performed by the Remote Metallography Group, Solid State Division.

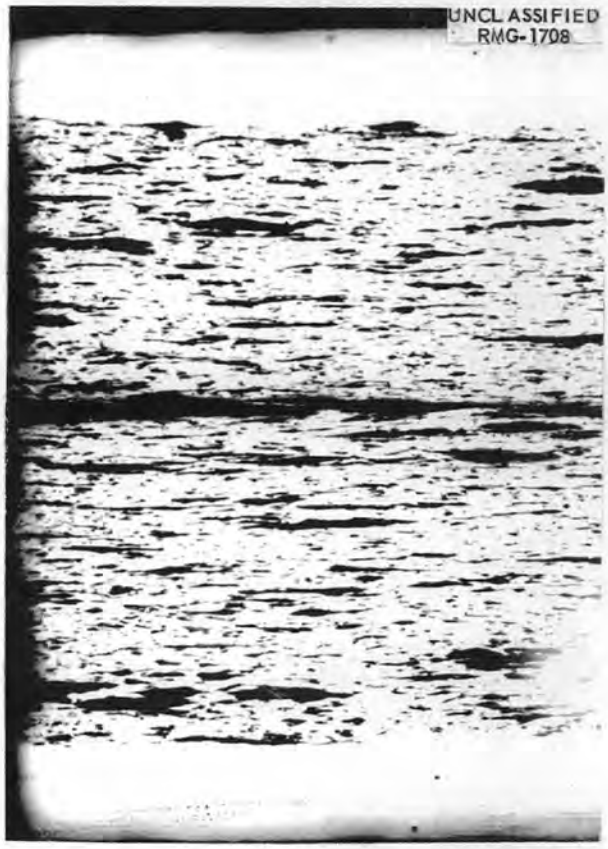

Fig. 10. BN–Ni Cermet Clad with Type 304 Stainless Steel. Irradiated to average B^{10} burnup of 38%. 75X. (Confidential with caption)

reaction zone between the type 304 stainless steel cladding and the core.[6] No increases in the amount of this reaction were observed as a result of irradiation. Irradiation of this material to 19% average B^{10} burnup revealed no damage other than the expected hardness increase (Figs. 12 and 13). When the irradiation was increased to 38% average B^{10} burnup, the material showed a slight general cracking throughout the core matrix (Fig. 14). However, this material suffered much less damage than the BN–Ni.

[6]M. R. D'Amore and J. H. Coobs, *ANP Quar. Prog. Rep. June 10, 1956*, ORNL-2106, p 169.

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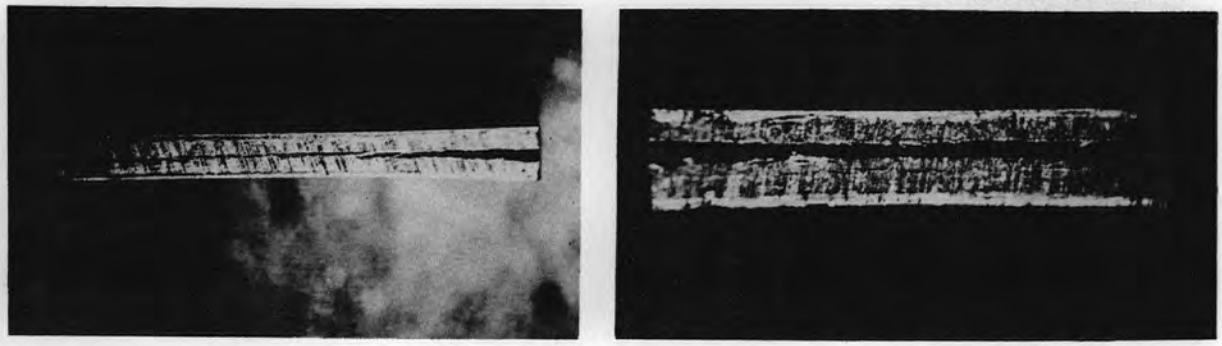

SIDE VIEW (4X) END VIEW (8X)

Fig. 11. BN–Ni Cermet Clad with Type 304 Stainless Steel. Irradiated to average B^{10} burnup of 38%. Reduced 25%. (Confidential with caption)

Table 8. Effect of Irradiation in the LITR on Dimensions and Hardness of BN–Ni and CaB_6–Fe Cermets Clad with Type 304 Stainless Steel

Cermet	Length Change (% increase)	Width Change (% increase)	Thickness Change (% increase)	Density Change (% decrease)	Increase in Hardness Number	
					Core	Stainless Steel Cladding
			19% Average B^{10} Burnup			
CaB_6–Fe[a]	<0.1	<0.2	<0.3	<0.2	10[b]	25[c]
BN–Ni[a]	<0.1	<0.2	<0.3	<0.2	100[c]	25[c]
			38% Average B^{10} Burnup			
CaB_6–Fe[d]	0.8	1.6	2.1	1.2	36.0[b]	55.0[c]
BN–Ni[d]	0.4	1.0	5.4	1.0	204.0[c]	47.6[c]

[a]Typical sample.
[b]Diamond pyramid hardness, 4-kg load.
[c]Knoop hardness number, 1-kg load.
[d]Average of three samples.

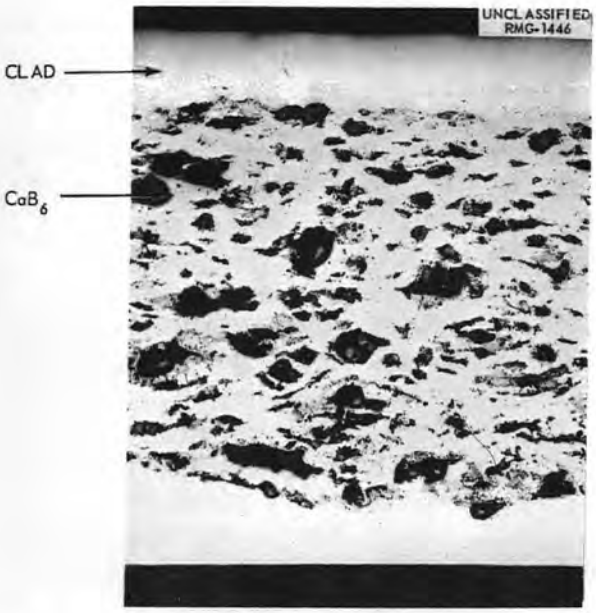

Fig. 12. CaB_6–Fe Cermet Clad with Type 304 Stainless Steel. Unirradiated. 75X. Reduced 27.5%.

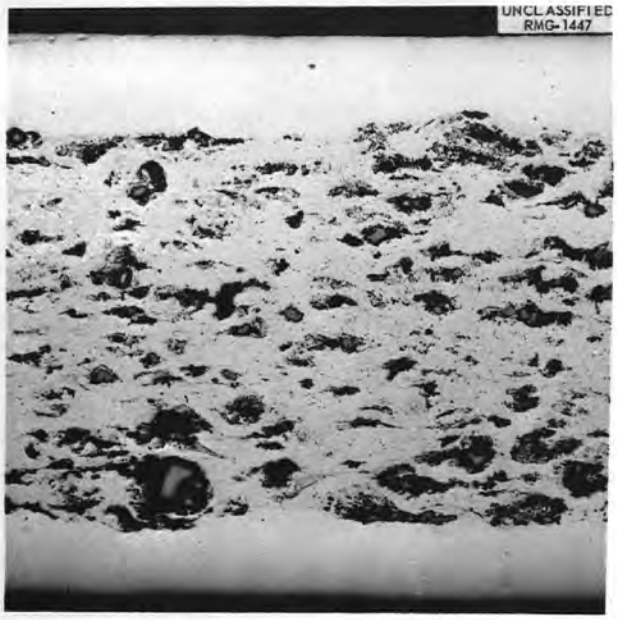

Fig. 13. CaB_6–Fe Cermet Clad with Type 304 Stainless Steel. Irradiated to average B^{10} burnup of 19%. 75X. Reduced 27.5%. (Confidential with caption)

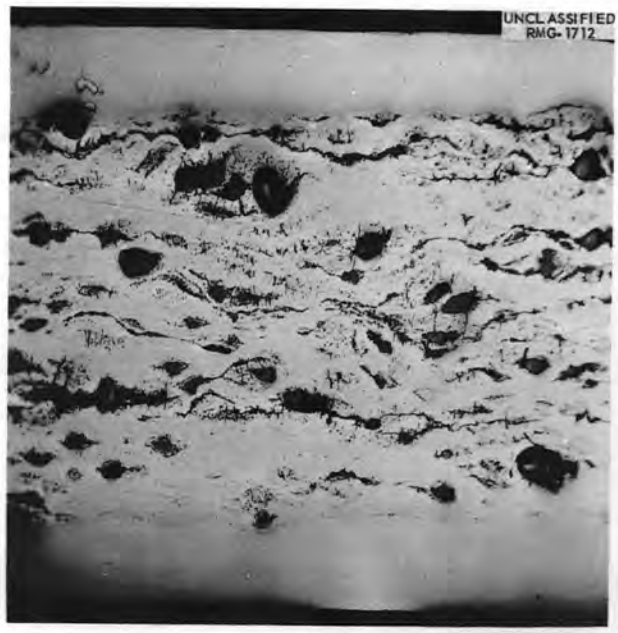

Fig. 14. CaB_6–Fe Cermet Clad with Type 304 Stainless Steel. Irradiated to average B^{10} burnup of 38%. 75X. Reduced 27.5%. (Confidential with caption)

STAINLESS-STEEL-CLAD COPPER–BORON CARBIDE

This clad cermet was proposed for use, together with the B_4C tiles, in the neutron shielding curtain of the molten-salt reactor. The shielding elements fabricated by the Metallurgy Division[7] were 0.1875 × 0.500 × 0.102 in. thick and clad on two faces. The composition was 6.6 wt % B_4C (–325 mesh), 93.4 wt % copper, clad with a 3-mil copper barrier over which was clad 7 mils of type 430 stainless steel. The core was exposed on the four remaining edges of the specimen. The samples were irradiated in an "A" piece in the MTR. Figures 15 and 16 show the components of the irradiation assembly. Three samples were mounted in a support grid with thermocouples attached (Fig. 15) and sealed under helium in an inner capsule C (Fig. 16). A heater made of platinum coils wound on an alumina form surrounded this capsule and was contained in a can B. The

[7] M. R. D'Amore, private communication.

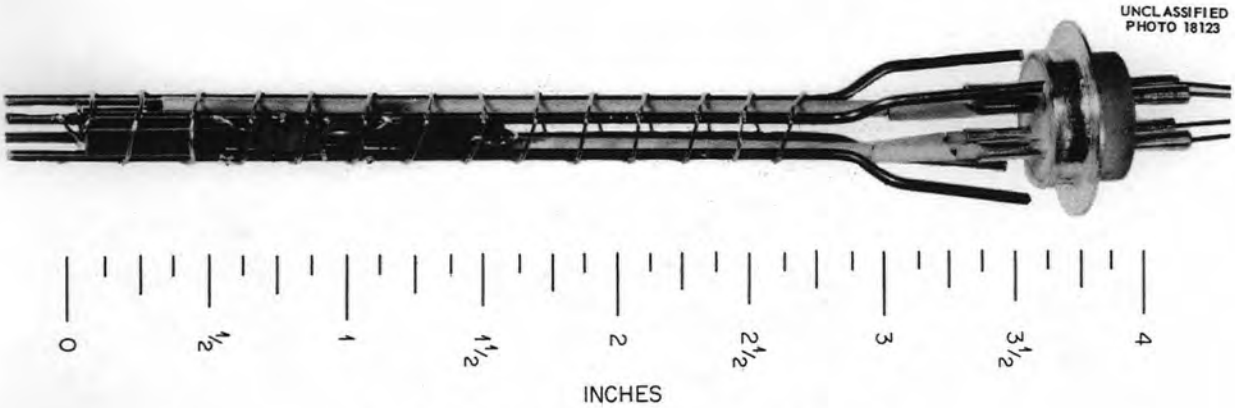

Fig. 15. Sample Support Grid for MTR Irradiations.

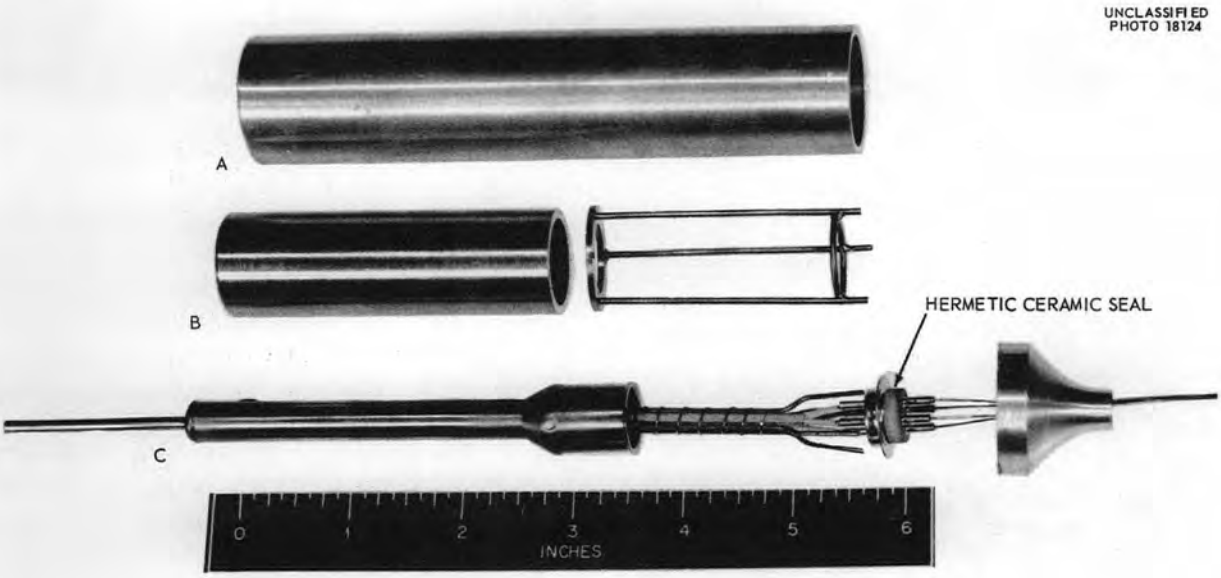

Fig. 16. Components of MTR Irradiation Assembly.

assembly was welded into an aluminum can A, with the thermocouples led out through a small aluminum tube to the top of the reactor. After irradiation, the samples were returned to ORNL for examination.

Prototype samples from a manufacturer were tested in a similar manner at higher temperatures. The irradiation histories of these samples are shown in Table 9. No cracking or separation of the cladding from the core was observed after an irradiation of 19% average B^{10} burnup at 300°C. Figures 17 and 18 show the Cu–B_4C material after an irradiation at 300°C to 19% average B^{10} burnup.

The irradiation (No. 127) at 420°C to 18% average B^{10} burnup resulted in core cracking and core-cladding separation (Fig. 19). Hardness measurements were made on the stainless steel cladding, copper cladding, and core after irradiation. The post-irradiation core hardness measurements are not reported on samples which suffered severe cracking. Table 10 summarizes the results of the hardness measurements.

The prototype material suffered core cracking and core-cladding separation similar to that experienced in irradiation No. 127. Figures 20–23 show side and end views of typical cracking. Dimensional changes are listed in Table 11. This

Table 9. History of Stainless-Steel-Clad Cu–B_4C Shield Material Irradiated in the MTR

Irradiation Number	Number of Samples	Average Temperature of Irradiation (°C)	Average B^{10} Burnup (%)	Number of Temperature Cycles	Damage
227	3	200	6	3	No cracking or core-cladding separation
327	3	300	19	7	No cracking or core-cladding separation.
127	3	420	18*	19	Longitudinal core cracking and core-cladding separation.
Prototype No. 12	1	870	12.5	8	Longitudinal core cracking and core-cladding separation
Prototype No. 13	1	870	21	7	Longitudinal core cracking and core-cladding separation.
Prototype No. 14	1	870	21	6	Longitudinal core cracking and core-cladding separation.
Prototype No. 17	1	870	21	8	Longitudinal core cracking and core-cladding separation.

*Determined by isotopic analysis; other values were calculated.

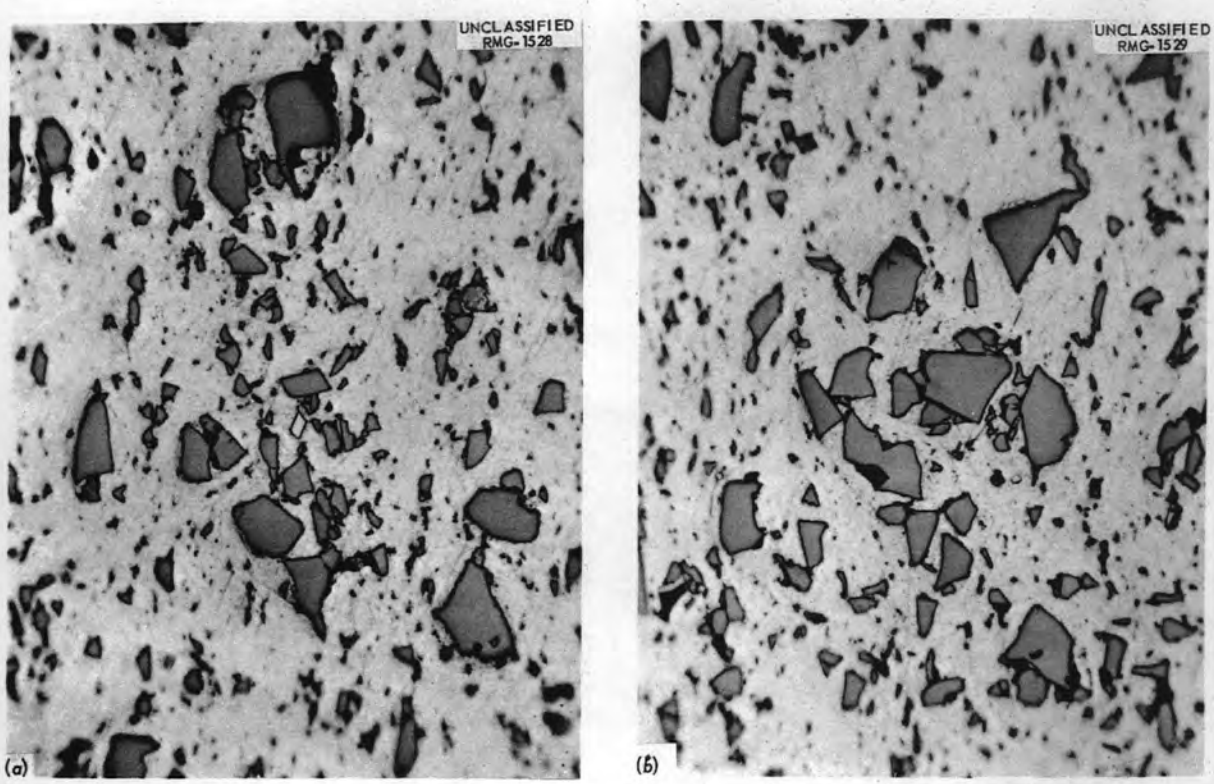

Fig. 17. Core Structure of Cu–B_4C Shielding Element. (*a*) Unirradiated. (*b*) Irradiated at 300°C to average B^{10} burnup of 19%. 500X. Reduced 22.5%. (Confidential with caption)

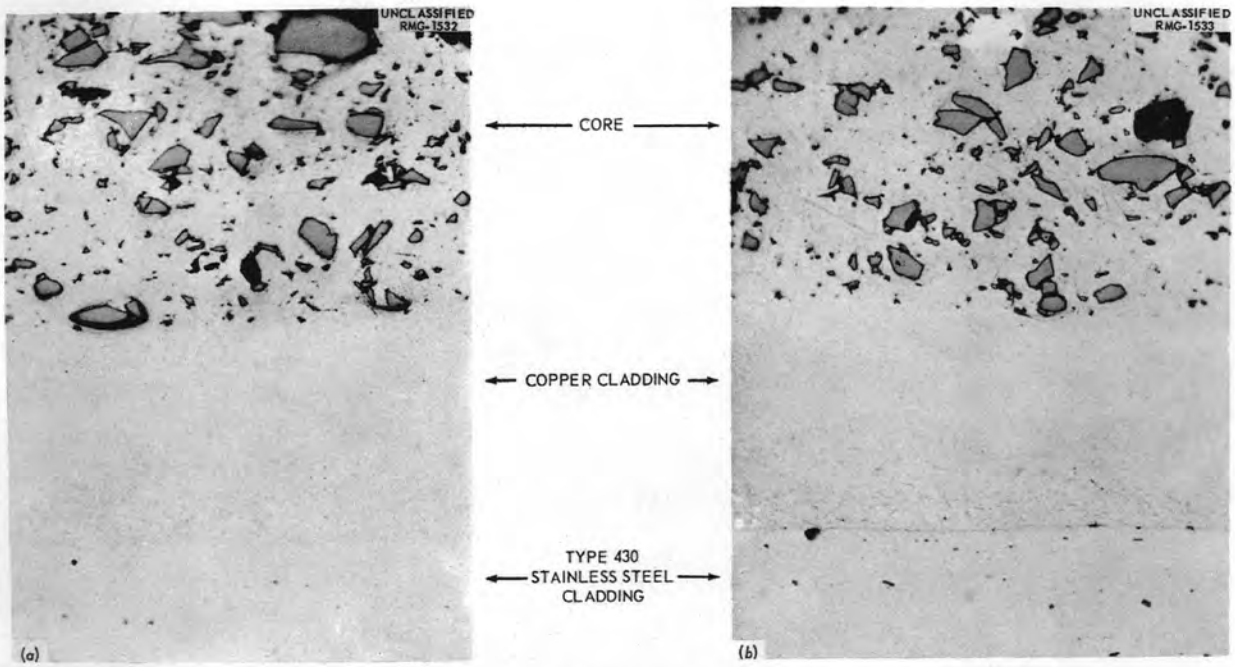

Fig. 18. Core-Cladding Interface of Cu–B_4C Shielding Element. (*a*) Unirradiated. (*b*) Irradiated at 300°C to average B^{10} burnup of 19%. 500X. Reduced 37.5%. (Confidential with caption)

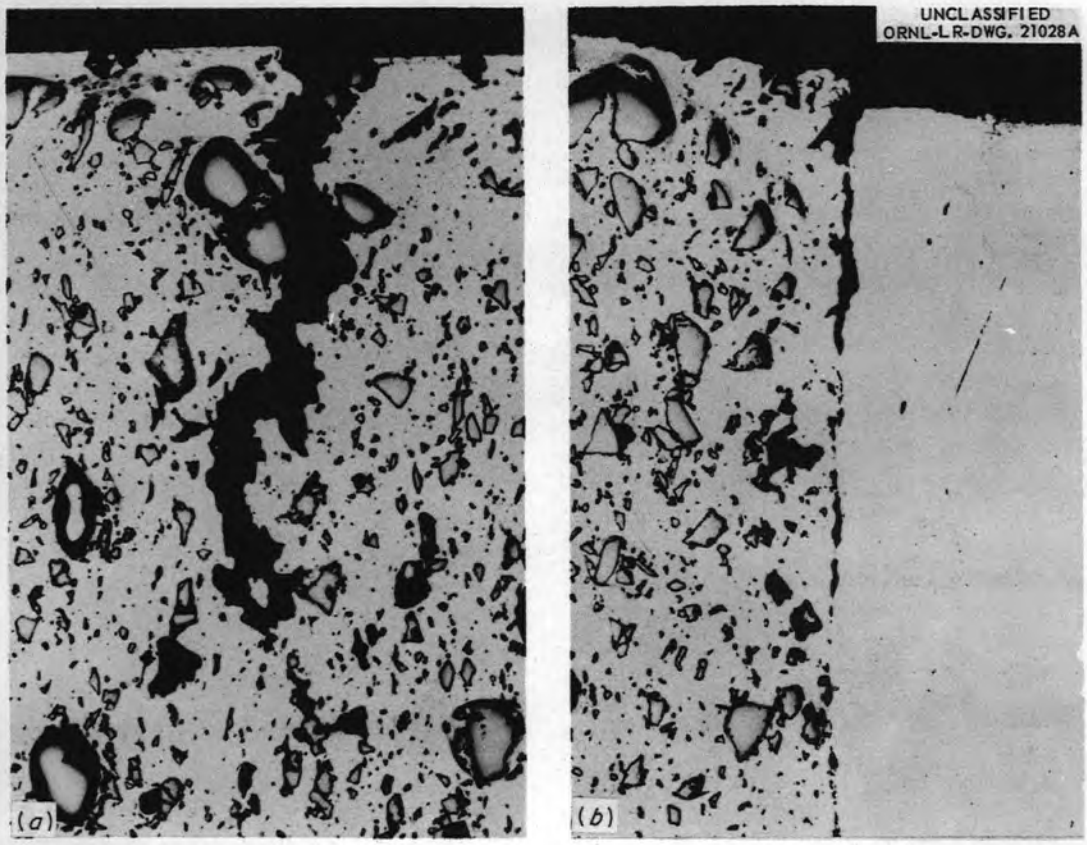

Fig. 19. Specimen of Cu–B_4C Irradiated at 420°C to Average B^{10} Burnup of 18%. (*a*) Typical crack in core. (*b*) Separation at interface of core and cladding. 250X. Reduced 12.5%. (Confidential with caption)

Table 10. Hardness Change in Irradiated Cu–B_4C

Irradiation Number	Average Knoop Hardness Number, 1-kg Load			Increase After Irradiation (%)
	Component	Unirradiated	Irradiated	
227	Stainless steel cladding	139	166	19
	Copper cladding	64	76	19
	Core	76	102	34
327	Stainless steel cladding	139	215	55
	Copper cladding	64	88	38
	Core	76	85	12
127	Stainless steel cladding	139	186	34
	Copper cladding	64	65	2

Fig. 20. End of Cu–B_4C Specimen No. 127-1 After Irradiation at 420°C to Average B^{10} Burnup of 18%, Showing Cracking. 13X. (Confidential with caption)

damage was thought to be primarily due to the thermal history of the irradiated samples rather than to the irradiation itself. Damage to the material due to thermal cycling occurs in the absence of irradiation and was confirmed by a laboratory experiment in which samples were cycled under a vacuum. In the laboratory experiment, more thermal cycles were required before damage resulted; however, the irradiated samples had experienced a different thermal gradient history, and

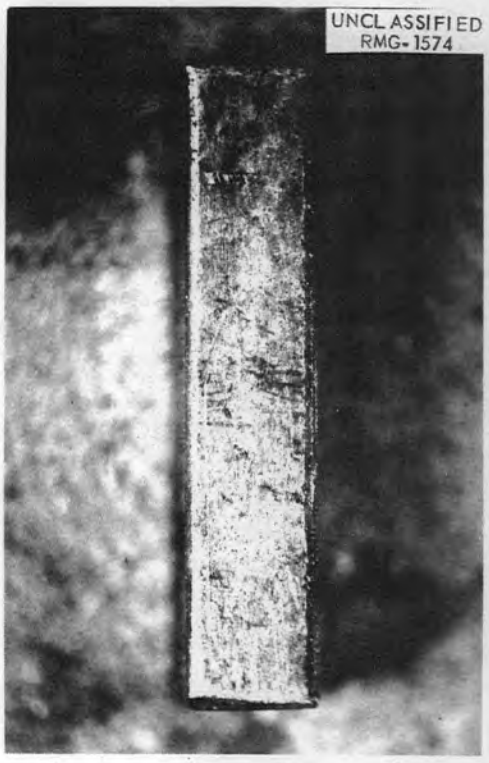

Fig. 21. Side of Cu–B_4C Specimen No. 127-1 After Irradiation at 420°C to Average B^{10} Burnup of 18%, Showing Cracking. 7X. (Confidential with caption)

this may account for the change with fewer cycles. Figures 24 and 25 show the core cracking and core-cladding separation caused by thermal cycling in the absence of radiation.

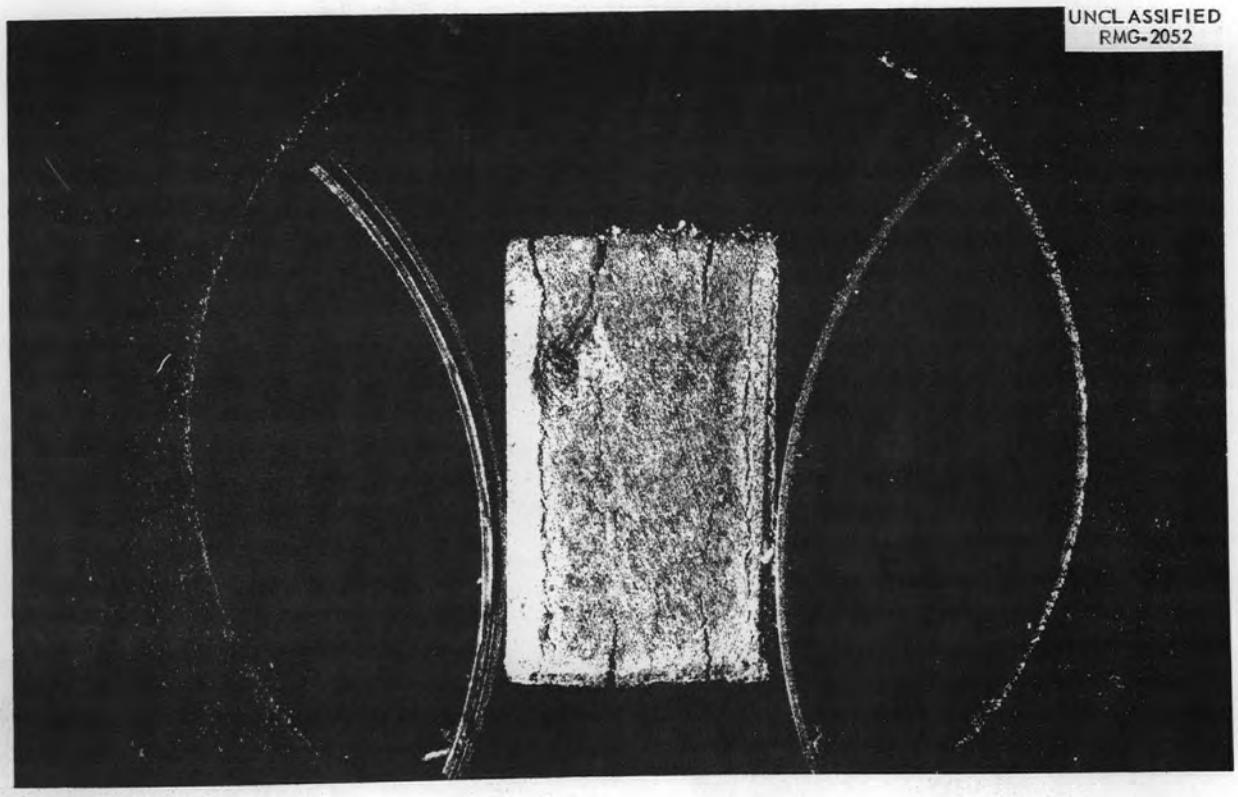

Fig. 22. End of Cu–B_4C Specimen No. 127-2 After Irradiation at 420°C to Average B^{10} Burnup of 18%, Showing Cracking. 13X. (Confidential with caption)

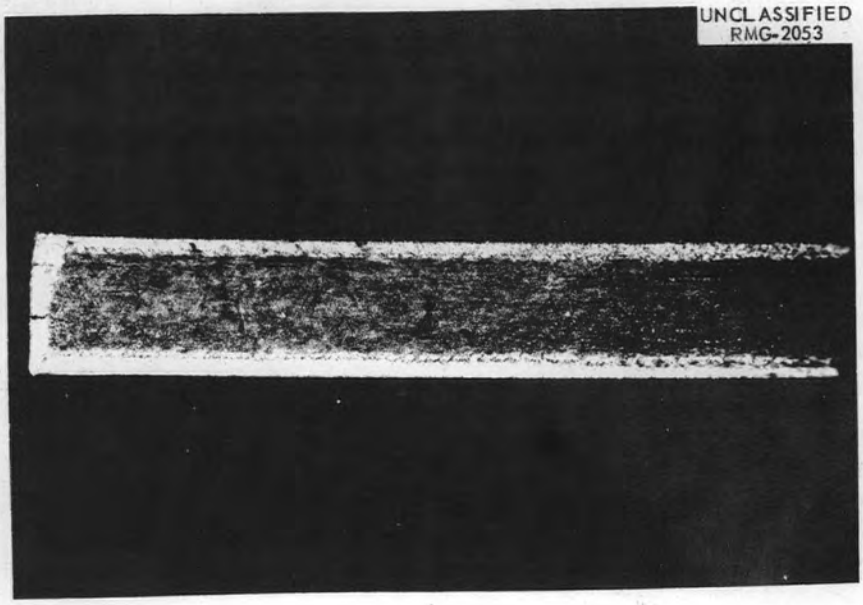

Fig. 23. Side of Cu–B_4C Specimen No. 127-2 After Irradiation at 420°C to Average B^{10} Burnup of 18%, Showing Cracking. 7X. (Confidential with caption)

Table 11. Dimensional Changes in Irradiated Cu–B_4C

Irradiation Number	Length Change (% increase)	Width Change (% increase)	Thickness Change (% increase)	Density Change (% decrease)
227[a]	<1	<1	<1	<1
327	<1	1.8	2.0	3.0[b]
127	0.5	0.8	2.3	2.3
Prototype No. 12	2.5	3.5	12.1	11.6
Prototype No. 13	3.5	7	21	16
Prototype No. 14	4.1	5	20	18
Prototype No. 17[c]	3.6	5	18	25

[a]Samples were slightly oxidized, which resulted in data scattering. There was essentially no change after irradiation.

[b]Bulk density.

[c]Irradiated with the stainless steel cladding removed.

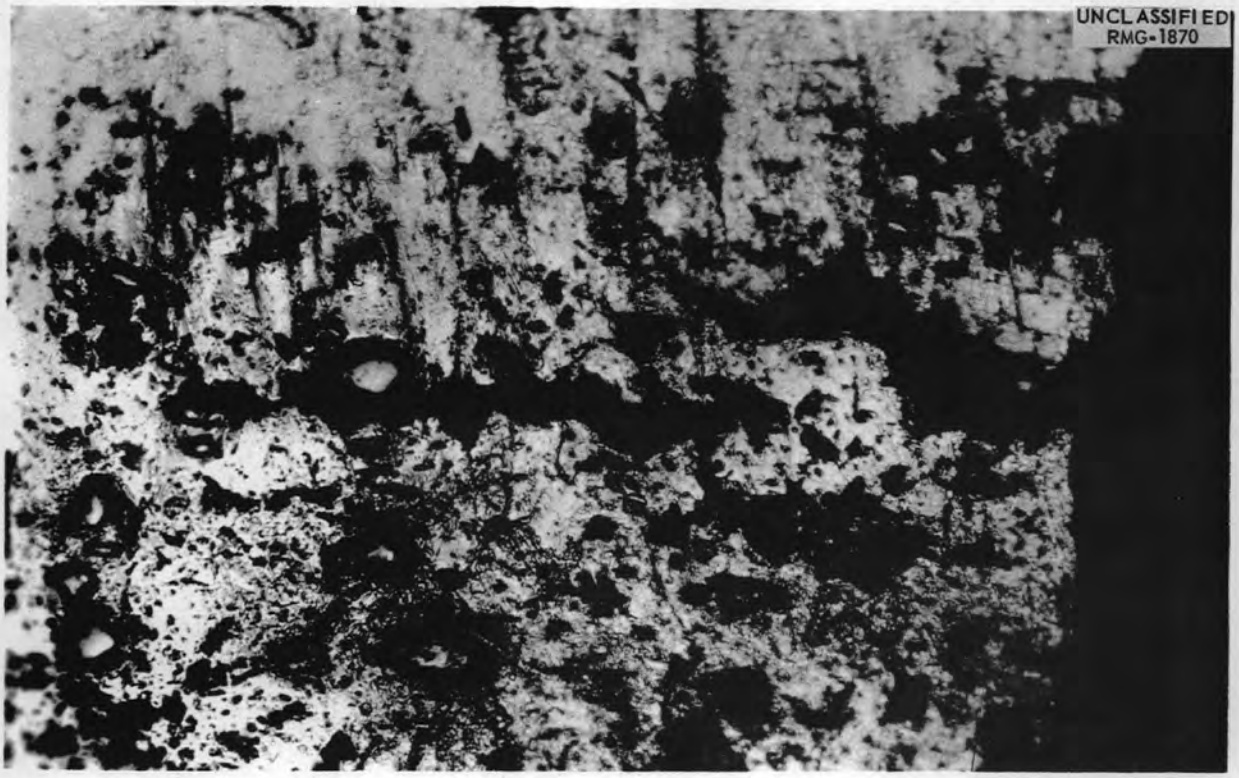

Fig. 24. Unirradiated Stainless-Steel-Clad Cu–B_4C Specimen After Thermal Cycling, Showing Cracking in Core. Treatment: 20 cycles from 75 to 600°C, 38 cycles from 100 to 870°C. 250X. (Confidential with caption)

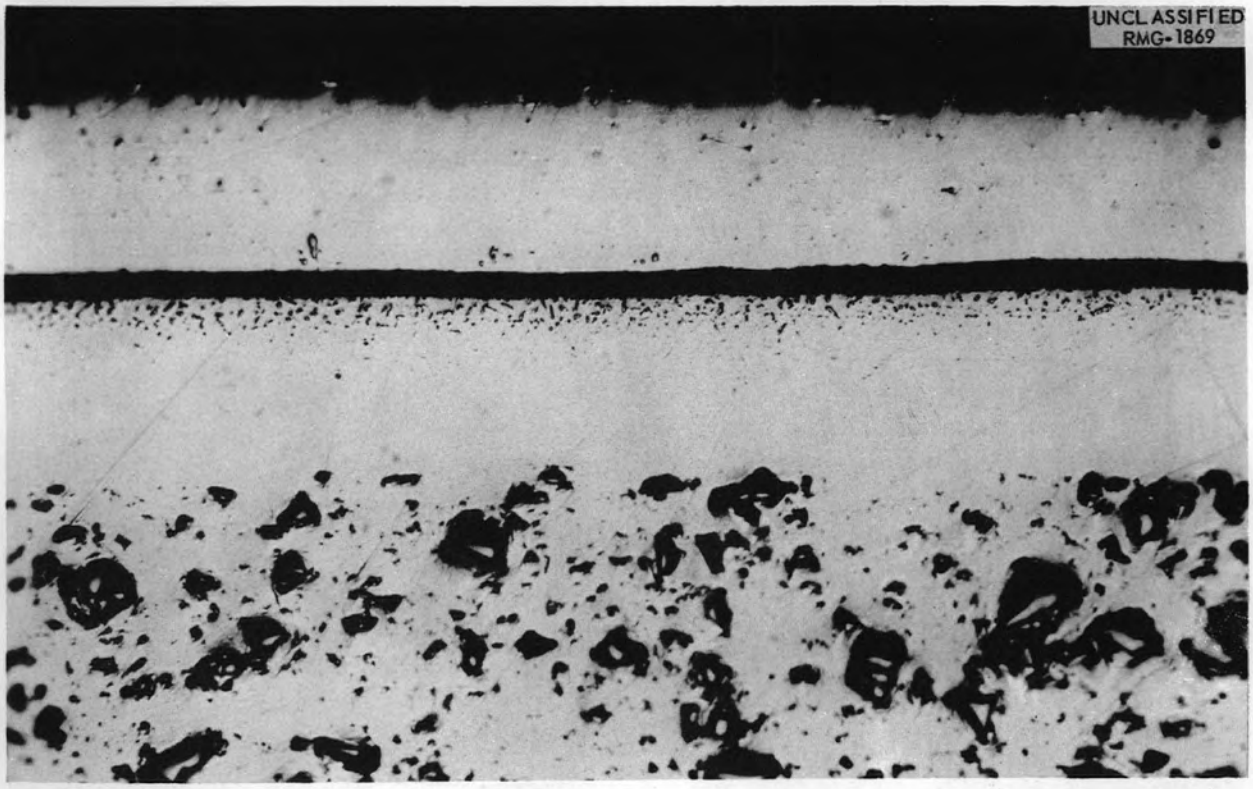

Fig. 25. Unirradiated Stainless-Steel-Clad Cu–B_4C Specimen After Thermal Cycling, Showing Separation of Cladding from Core. Treatment: 20 cycles from 75 to 600°C, 38 cycles from 100 to 870°C. 250X. (Confidential with caption)

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