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DEVELOPMENT AND PROPERTIES OF
URANIUM MONOCARBIDE CERAMTS

Final Report

NOTE

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For:

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September 17, 1956

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DEVELOPMENT AND PROPERTIES OF URANIUM MONOCARBIDE CERAMETS

ABSTRACT

Uranium monocarbide-Zircaloy II alloy ceramets were developed and tested for chemical and physical properties. It was demonstrated that pure uranium monocarbide can be prepared by vacuum arc melting techniques. Following melting, the comminution, hot pressing, and corrosion behavior of dense monocarbide has been studied. The preparation of uranium monocarbide-Zircaloy II cermet bodies was investigated by means of hot pressing, cold pressing and sintering, warm pressing, extrusion, and hot rolling. The corrosion resistance of the ceramets was related to such variables as composition, preparation technique, and powder size. 30 per cent uranium monocarbide, 70 per cent zircaloy II ceramets withstood corrosion tests in 680°F water. Ceramets having above 30 weight per cent uranium monocarbide were not corrosion resistant.

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DEVELOPMENT AND PROPERTIES OF URANIUM MONOCARBIDE CERAMETS

I. INTRODUCTION

A. Objectives

The major objective was the development of uranium monocarbide-Zircaloy II ceramets containing a maximum amount of dispersed uranium monocarbide. A method of preparing pure granular uranium monocarbide was developed for this cermet investigation. It was found that the highly pure material could be prepared in suitable amounts by vacuum arc melting in a non consumable electrode furnace. Following this, the procedures for comminution, handling, and blending of UC and Zircaloy II powders were investigated.

Five different processes were explored as means to consolidate the uranium monocarbide and Zircaloy II powders. These were hot pressing, warm pressing, cold pressing followed by sintering, extrusion and hot rolling. Experimental ceramets were subjected to hot water corrosion testing.

The composition ranges of cermet bodies were between 10 per cent and 70 per cent by weight uranium monocarbide. The 30 weight per cent composition was the highest carbide content that withstood tests in 680°F water.

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B. Scope

The corrosion resistance of these cermet compositions depends on the variables introduced by the preparation technique. The more important variables are the following: 1. the degree of contamination of the Hircaloy II matrix, 2. the extent of diffusion between the carbide and the matrix, 3. the particle size and uniformity of dispersion obtained in the uranium monocarbide phase, and 4. the presence or absence of porosity in the Hircaloy II matrix.

All of these factors have been considered in relation to specific processing techniques. Because of the number of variables involved, it has not been possible to conduct a detailed investigation of each variable separately. For example, the various techniques to obtain uniform dispersions such as ball milling and cone blending using volatile blending agents have not been fully investigated. Similarly, the effects of particle size upon corrosion resistance have been investigated only in relation to hot pressing techniques.

Within these limits the program has been conducted by following lines of development that have appeared most logical on the basis of available data. For example, the criteria governing particle size selection for the hot pressing technique were applied directly to hot rolling without additional exploratory experiments. In this instance, such additional experimentation might permit the incorporation of an increased amount of uranium monocarbide in the hot rolling process.

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It has been established that diffusion between Zircaloy II and uranium monocarbide proceeds rapidly above 1000°C. Extensive diffusion between the carbide phase and the matrix has a deleterious effect upon corrosion resistance. In addition, the corrosion resistance of uranium monocarbide-Zircaloy II cement bodies is sensitive to composition, particle size of the dispersed phase, degree of dispersion, matrix porosity, and the extent of contamination during processing. A composite containing 30 per cent by weight uranium monocarbide has withstood testing in 680°F water during this investigation.

II. EXPERIMENTAL PROCEDURES

A. Powder Preparation

1. Uranium Monocarbide

Uranium monocarbide prepared by arc melting was used exclusively during this program. Initially, apparatus was assembled to duplicate the process for methane carburization of uranium as developed by Lita.¹ At the same time, the preparation of the monocarbide by arc melting was explored. The arc melting method of preparation has proven to be the most feasible to obtain the required quantities of uranium monocarbide and the Lita method was not carried forward.

¹ L. N. Lita, Uranium Carbides-Their Preparation, Structure, and Hydrolysis (Technical Information Division, Oak Ridge, Tennessee, Atomic Energy Commission, April 26, 1950).

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To produce uranium monocarbide by the arc melting technique, a non-consumable electrode using a water cooled copper crucible was used. Helium was the protective atmosphere used. A high purity graphite water cooled electrode, held negative, was employed. Melting required a current of about 590 amperes at 40 volts for a 100 gram charge.

Initially, melts covering a range of carbon contents were prepared so that microstructures adjoining the monocarbide in the uranium-carbon system, as determined by Mallett, Gerds, and Nelson,² and the monocarbide itself could be identified. Analyses of some melts prepared for this work are given in Table I. Figures 1 to 7 show the microstructural changes with varying carbon contents. From these studies in conjunction with chemical analysis, it was found that a furnace charge containing 4.85 per cent spectrographic electrode carbon was required to prepare the monocarbide containing 4.79 per cent carbon.

2. Commixtion to Form Uranium Monocarbide and Zircaloy II Powders

The preparation, handling and processing of uranium monocarbide and Zircaloy II powders was performed inside a dry box under helium atmosphere.

Two methods of crushing uranium monocarbide to powders were explored: 1. ball milling, and 2. crushing in a "diamond" mortar as reported by Litz.³ In comparing the two methods, the use of the diamond

² M. W. Mallett, A. F. Gerds, and H. R. Nelson, The Uranium-Carbon System (Metzger Memorial Institute, Report No. MMI-53), April 1, 1951.

³ Litz, op. cit.

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TABLE I

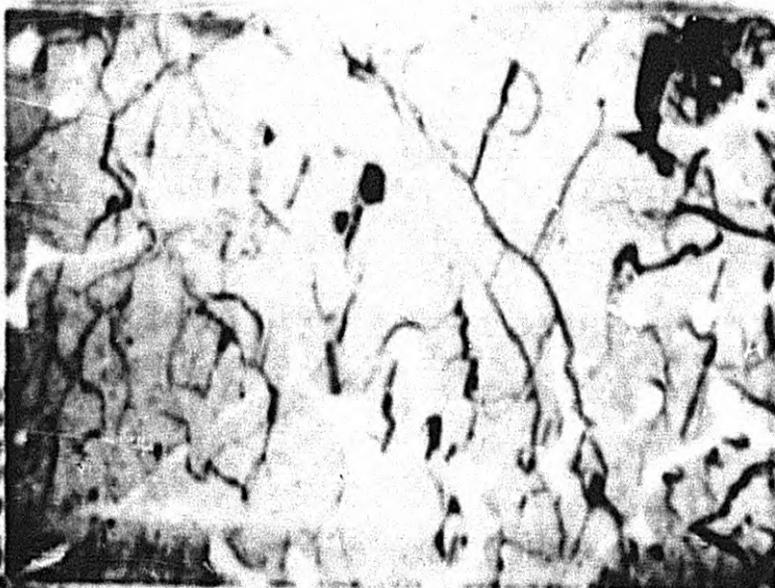
Chemical Analyses of UC Alloys

Sample Position	Chemical Analysis (wt % C)			
	Melt No. 1000	Melt No. 1001	Melt No. 1002	Melt No. 1004
Center Top	4.98	5.00	5.91	6.85
Center Bottom	4.40	4.96	5.77	6.86
Edge "A"	4.29	5.11	5.83	7.01
Edge "B"	4.60	5.09	5.94	6.86
	Average 4.58	Average 5.04	Average 5.86	Average 6.89

Sample Position	Chemical Analysis (wt % C)		
	Melt No. 1005	Melt No. 1006	Melt No. 1007
Center Top	9.04	3.80	4.78
Center Bottom	8.78	3.80	4.87
Edge "A"	8.65	3.74	5.00
Edge "B"	8.82	3.78	4.73
	Average 8.82	Average 3.78	Average 4.84

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Negative (amber 1120)
Etchant: dilute HF

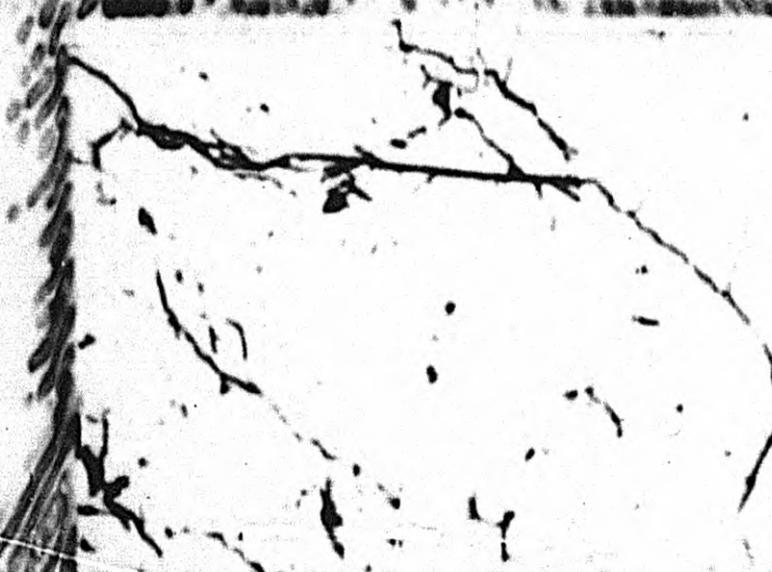
Figure 1

Fig. 1 250

Alloy: U-3.0 wt % C

Treatments: 1500°C, 30 minutes; 1700°C, 10 minutes; quenched.

The structure consists of uranium in UC grains boundaries.



Negative (amber 1120)
Etchant: dilute HF

Figure 2

Fig. 2 250

Alloy: U-3.0 wt % C

Treatments: 1500°C, 30 minutes; 1700°C, 10 minutes; quenched.

No alpha uranium is seen in this structure (UC), although analysis indicates some should be present.

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Negative Number 30
Etchant: dilute

Alloy: U-4.4 wt % G
Treatment: 1500°C, 30 minutes; 1700°C, 10 minutes; quenched.
A fine precipitate believed to be UC₂ is seen in the matrix.



Negative Number 31
Etchant: dilute

Alloy: U-4.4 wt % G
Treatment: 1500°C, 30 minutes; 1950°C, 10 minutes; quenched.
The appearance is very similar to that of Figure 1. The increased temperature effect.

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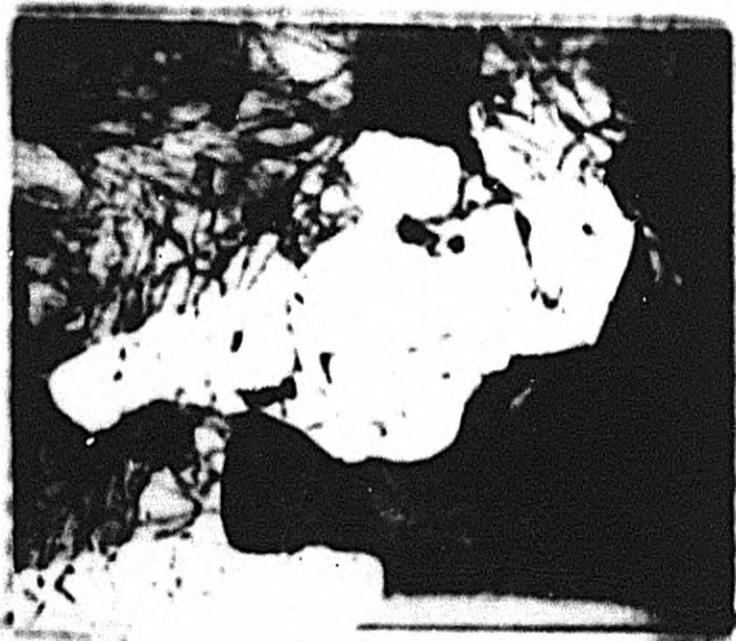
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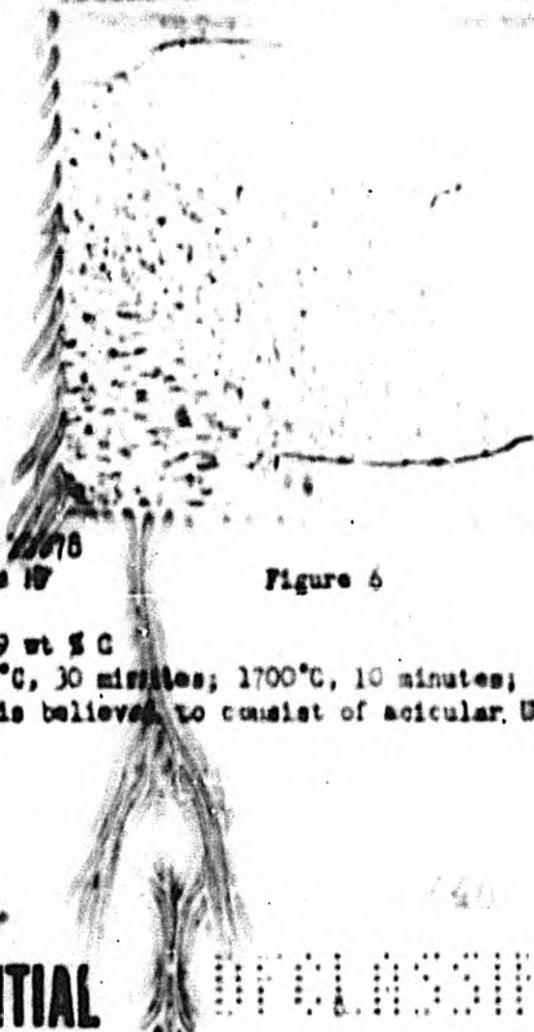


Negative Number 10882
Etchant: dilute HF

Figure 5

Mag. X 250

Alloy: U-5.04 wt % C
Treatments: 1500°C, 30 minutes; 1700°C, 10 minutes; quenched.
The structure consists of UC containing precipitated UC₂ (light etching acicular phase).



Negative Number 10878
Etchant: dilute HF

Figure 6

Mag. X 250

Alloy: U-6.9 wt % C
Treatments: 1500°C, 30 minutes; 1700°C, 10 minutes; quenched.
This structure is believed to consist of acicular UC and UC₂.

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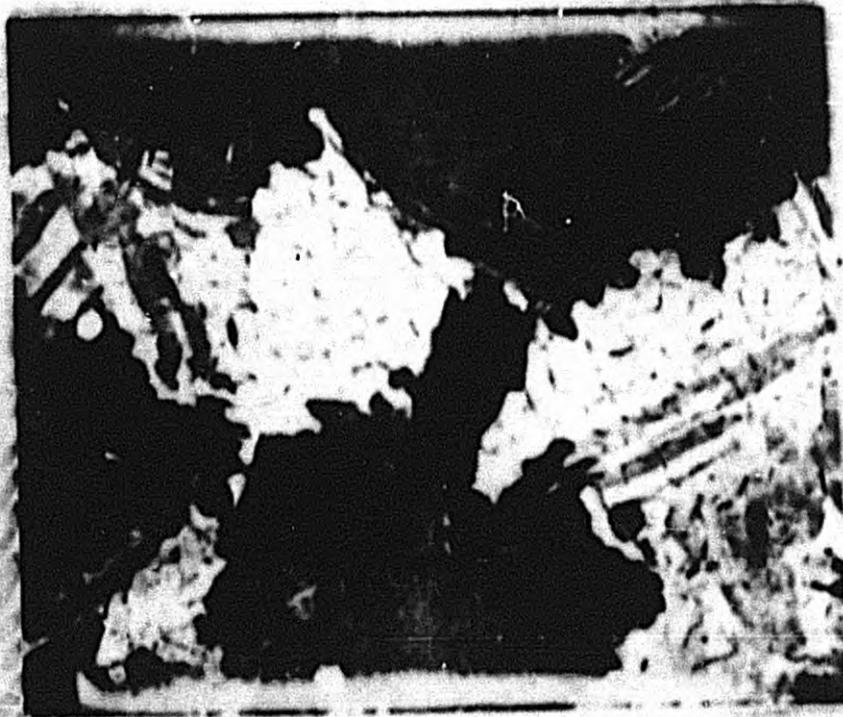
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Negative Number 10880
Etchant: dilute HF

Mag. X 250

Figure 7

Alloy: U-8.8 wt % C

Treatment: 1500°C, 30 minutes; 1700°C, 10 minutes; quenched.

This structure is believed to consist of UC_2 containing some precipitated UC.

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mortar was found to be most practical to prepare the relatively small batches of material required for this investigation. All crushing was done under helium atmosphere. Typical analysis for UC powders prepared by this method are shown in Table II.

Two types of Zircaloy II powder were used during the program. These were formed by hydrogenation of Zircaloy II sheet, as described by Angier, Hausner, and Kalish for zirconium,⁴ and powders prepared by filing Zircaloy II bar stock under helium. The Zircaloy II hydride powder was prepared to specifications by the Sylvania Electric Company.

Corrosion tests of the carbide and of 100 per cent Zircaloy II powder compacts were performed (Table III). It was demonstrated that any intrinsic corrosion resistance of the monocarbide itself was negligible. At the same time, it was determined that the corrosion performance of the Zircaloy II matrix to be used in the cermet was adequate. Figure 8 illustrates the appearance of a typical Zircaloy II specimen prepared from the hydride powder after corrosion tests.

3. Special Surface Treatments of Uranium Monocarbide Powder for Diffusion Barriers

During the course of the program, several means of inhibiting diffusion between uranium monocarbide and Zircaloy II were explored. Metallic coatings in the form of electrodeposited nickel, Kanigen nickel plate, tin coatings formed by wiping and dipping, vacuum

⁴ H. S. Kalish, H. H. Hausner, and R. P. Angier, The Physical Properties of Sintered Zirconium (US Atomic Energy Commission, SEP-44), November 20, 1951.

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TABLE II
Typical Analysis of UC and Zircaloy II Powder Materials

Material	H ₂	O ₂	N ₂	C
UC powder, -16 + 32 mesh, as crushed	70 ppm	0.37 %	0.019 %	4.67 % average
UC powder, -16 + 32 mesh, as hot pressed 1500°C	less than 1 ppm	0.27 %	0.64 %	4.67 % average
Zr II hydride powder, -100 mesh, as received ^o	approx. 2.1 %	0.004 %	0.019 %	not detected
Zr II hydride powder, -28 + 80 mesh, as received ^o	approx. 2.1 %	0.0097%	0.0096%	not detected
Zr II powder prepared by filing hot rolled bar under helium atmosphere, then hot pressed at 1200°C	53 ppm	0.11 %	0.039 %	0.014 %

^o Material prepared by The Sylvania Electric Company.

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TABLE III

Corrosion Performance of Typical Pure UC and Zircaloy II Bodies

Test Material	Test Condition	Initial Weight (grams)	Weight Loss (grams)	Time (hr)	Weight Loss ^a Mg/cm ²	Weight Loss ^a Mg/cm ² /hr
Arc melted UC as arc melted	Distilled water boiling at 212°F	3.00 grams	3.00	0.42	980.0	2.360
Specimen No. H-100-Zr-2 prepared from -100 mesh Zr II hydride, hot pressed 1100°C, 6,000 psi, helium	distilled water, 680°F	26.6583	+0.0614	32.0	+5.97	0.186
Specimen No. H-100-Zr-31, Zr II saw filings, -100 mesh, hot pressed 1200°C, 6,000 psi, helium	Distilled water, 680°F	12.0415	+0.0036	223	+0.35	+1.56 x 10 ⁻³
Specimen No. H-100-Zr II-6, -100 mesh Zr II hydride hot pressed 1350°C, 6,000 psi, helium	distilled water, 680°F	15.1092	-0.0718	114	-7.0	4.86 x 10 ⁻²
1/8 inch thick Zircaloy II strip, used for making powder	distilled water, 680°F	5.6626	-0.003	72	-0.429	5.96 x 10 ⁻³

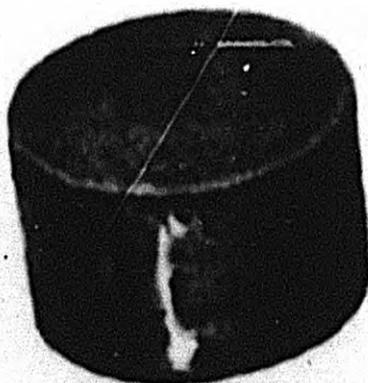
^aCalculated from estimated surface area at beginning of test.

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Negative Number 2177

Figure 8

Mag. X 3 diameter

Materials: Prepared from -100 mesh Zircaloy II hydride powder, hot pressed at 1100°C, 6,000 psi, helium atmosphere. The appearance is shown after testing for 48 hours in boiling water followed by 72 hours in water at 600°F.

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fusion of tin with an active flux in the presence of UC, and indium applied by wiping were examined. These elements are not carbide formers and hence might act as barriers between the uranium monocarbide and the Zircaloy II matrix. Use of a high melting metal as a barrier was tried also. Chromium plating of UC was studied to explore that approach. The plating experiments are described in Table IV. Table V lists the experiments using tin with a flux. The wiping experiments are illustrated in Figures 9 and 10.

In order to activate the UC surface preparatory to the coating experiments, a series of cleaning solutions intended to strip surface oxide films were explored. These are described in Table VI. These experiments showed that concentrated nitric acid does not rapidly dissolve UC. Instead, a black surface film presumed to be oxide is produced. After this treatment the reaction of UC with room temperature water is inhibited. Following this development, the ability of the surface film produced by concentrated nitric acid to inhibit diffusion between UC and Zircaloy II at high temperature was examined. Diffusion was not found to be appreciably inhibited, however. This is illustrated in Figure 11.

4. Blending and Mixing Techniques

The uniformity with which uranium monocarbide is dispersed in the Zircaloy II matrix to form a cermet is one of the important factors which affect corrosion behavior. Non-uniformity can appear as either occasional particle segregation of the UC or as a gross separation of the UC and Zircaloy II powders. When this segregation was present, no valid evaluation of corrosion behavior for a particular composition could be made.

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TABLE IV
Uranium Monocarbide Plating Experiments

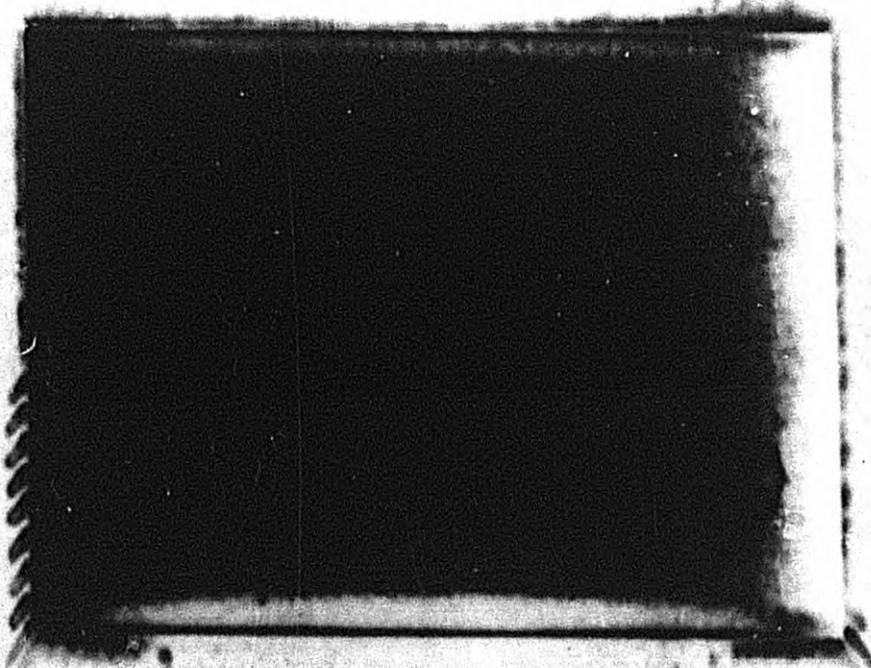
Plating Solution	Plating Conditions	Results
Alkaline Kenigen Nickel	810°Y (As recommended)	Did not plate; UC attached after 5 to 10 minutes.
Nickel Chloride - 30 g/l		
Sodium Hypophosphite - 10 g/l		
Sodium Citrate - 100 g/l		
Ammonium Chloride - 50 g/l		
Nickel Sulphate	75°Y - 90°Y Ni anode; Cu and Zn holders for UC explored; stirring action explored using magnetic stirrer.	Successful deposition of Ni on about 1% of -16 + 32 mesh UC particles held in stainless basket with stirring action.
Nickel Sulphate Hexahydrate - 16 cc/gal		
Ammonium Chloride - 3 cc/gal		
Boric Acid - 4 cc/gal		
Chromic Acid	75°Y	UC Attached
Chromic Acid - 53 cc/gal		
Sulphuric Acid - 0.53 cc/gal		

TABLE V
Tin Wetting Experiments

Flux	Temperature	Cu	Stainless Steel, in Passive State	Uranium Metal, HNO ₃ Pickled	UC, Emery Papered, 1/2 in. Particles
70% SnCl ₂ 30% NH ₄ Cl	275°C	Yes	No	No	No
70% SnCl ₂ 30% NH ₄ Cl	350°C	Yes	Yes	No	No
50% SnCl ₂ 25% NH ₄ Cl 25% NaCl	370°C	Yes	Yes	No	No
50% SnCl ₂ 25% NH ₄ Cl 25% NaCl	370°C	Yes	Yes	Probable	No

In the last two experiments, NaCl was added in order to stabilize the flux, as it tends to decompose at higher temperatures.

To explore the fusion of tin with UC and an active flux, a mixture containing 50% Sn shot and 50% SnCl₂ by weight was prepared. This mixture was brought to 700°C under vacuum in a molybdenum boat containing 1/2 inch diameter pieces of UC. The UC had to be cleaned using emery paper under helium atmosphere. No wetting resulted in this experiment.



Negative Number 12623

Figure 9

Mag. 1/2 X diameter

Materials used in tin wiping experiment; UG granule is at top; 99.99% pure tin slab is at bottom. No signs of tin being wiped on UG after vigorous rubbing could be found.



Negative No. 1222

Figure 10

Mag. 1 X diameter

Materials used in indium wiping experiment. The granule is at the left, indium wire is at the right. After vigorous rubbing, no indium was detected on the UC surface.

TABLE VI

UG Cleaning Experiments

Cleaning Solution	Temperature	Time	Results
Concentrated HCl (37% HCl)	Room temperature (70°F)	5 - 30 minutes	UG attacked
Dilute HCl (approx. 25% HCl)	Room temperature (70°F)	5 - 30 minutes	UG attacked
Concentrated HNO ₃ (70% HNO ₃)	Room temperature (70°F)	Up to 2 hours	UG particles are blackened after the first minute.
Dilute HNO ₃ (46% HNO ₃)	Room temperature (70°F)	5 - 10 minutes	UG particles corrode after 5 - 10 minutes.
Concentrated H ₂ SO ₄ (96% H ₂ SO ₄)	Room temperature (70°F)	5 - 10 minutes	UG attacked
Dilute H ₂ SO ₄ (64% H ₂ SO ₄)	Room temperature (70°F)	5 - 10 minutes	UG attacked
Chromic Acid Bath 24 oz Cr ₂ O ₃ 4 oz H ₂ SO ₄ per gallon	Room Temperature (70°F)	-	Brightens UG and will remove black film produced by concen- trated HNO ₃ .



Figure 11

Negative Number 12517
Etchants: 60% Glycerin
20% HNO₃
20% HF

Mag. 150 X diameter

Material: Uranium monocarbide-Zircaloy II diffusion couple. Initially, a uranium monocarbide granule was treated in HNO₃ to produce a surface oxide film. The UC was then surrounded by Zircaloy II powder and the composite hot pressed at 800°C, 6000 psi. This was followed by vacuum annealing for one hour at 1200°C.

Comments: The surface film has not interrupted the diffusion process significantly. Islands of a foreign microconstituent have formed in the Zircaloy II adjacent to the uranium monocarbide. The Zircaloy II is the light area to the right.

No practical means is known by which an absolute uniform dispersion could be attained, however. This means that some variation in carbide particle dispersion will always be present.

Three techniques to blend uranium monocarbide and Zircaloy II powders were considered. These were blending by hand or mechanical blending using ball milling or cone blending. The hand blending technique was adapted as being most practical. This was due to problems of contamination and attrition of UC being associated with ball milling and cone blending. These are largely avoided by hand blending. Equal if not better dispersions could be obtained by this method using small batches of material. The adoption of this technique allowed more effort to be directed toward other objectives. Hand blending was performed under a helium atmosphere inside a dry box. The suitably prepared powders were mixed together dry on a watch glass until uniformly dispersed. A stainless steel spatula was used for blending. When blended, the powder was transferred to the pressing mold or other container using a small spoon. It was important to avoid having the blended powders fall freely into the die cavity because segregation could occur at this point. Figure 12 illustrates the uniformity that can be obtained by this blending method.

B. Processing

1. Hot Pressing

The hot pressing technique offers the advantage of achieving densification without long heating periods at elevated temperatures.

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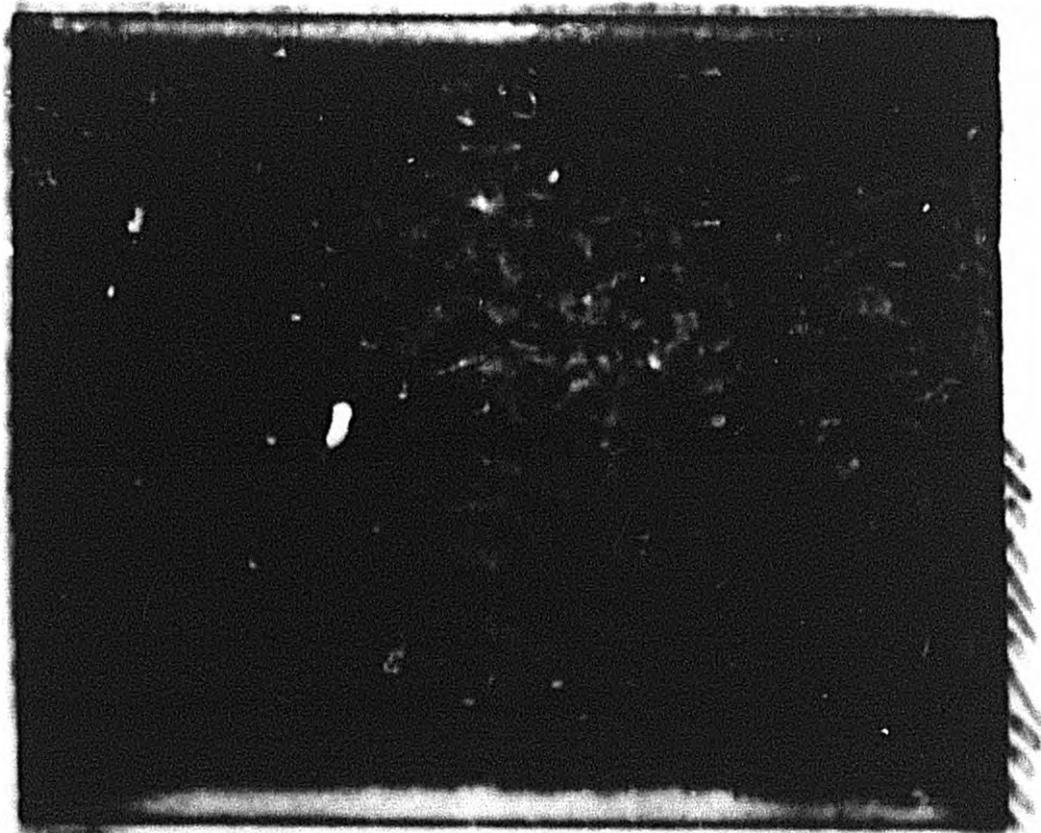


Figure 12

Negative Number 11310
Unetched

Mag. 0.5 X diameter

Material: Uranium monocarbide - Zircaloy II cement dispersion formed by hand blending and hot pressing. -100 mesh Zircaloy II hydride powder, hand blended with -20 mesh and down US powder, hot pressed 1200°C, 6000 psi.

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The apparatus consisted of hard carbon punches machined to fit high purity graphite molds. This assembly was insulated and heated by means of a 15 KVA high frequency induction machine. Pressure was applied by a hydraulic ram. The entire assembly was enclosed under a Pyrex bell jar. The hot pressing apparatus is schematically represented in Figure 1).

A 5/8 inch diameter and 1/2 inch in length standard specimen was used. A punch pressure of 6,000 psi was standard also, this being the maximum allowable stress for the hard carbon punches. The helium atmosphere was maintained by using high flow rates. Oxygen and nitrogen contamination were as indicated in Tables II and III. The time at peak temperature during hot pressing was between 30 to 60 seconds. The heating rate was approximately 120°C per minute. Approximately ten minutes were required to heat a compact to 1200°C.

2. Cold Pressing and Sintering

Cold pressed cermet specimens were made using steel punches and dies. Punch pressures used were in the range from 25,000 to 150,000 psi. Sintering temperatures were explored between 1000°C and 1300°C for periods of one hour. Sintering was carried out in a vacuum furnace using a molybdenum foil resistance heating element (Figure 1b). A vacuum of 0.01 μ (Hg) was obtained using this furnace. During the outgassing in the initial sintering period, sintering pressures sometimes ranged as high as 0.5 to 1.0 μ , however.

HOT PRESSING APPARATUS

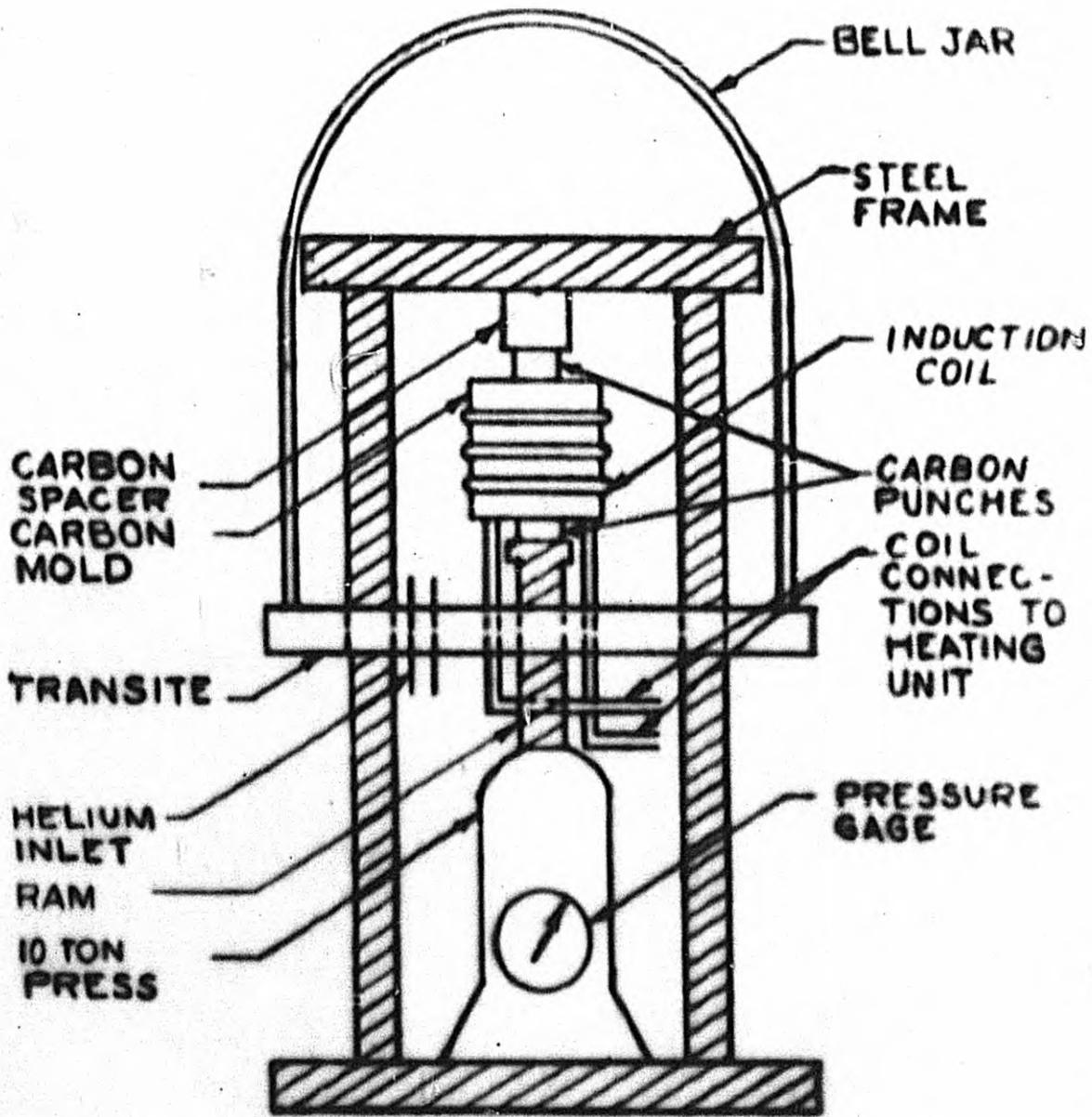


Figure 13 - Diagram of the Hot Pressing Apparatus

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**HIGH TEMPERATURE VACUUM RESISTANCE
FURNACE**

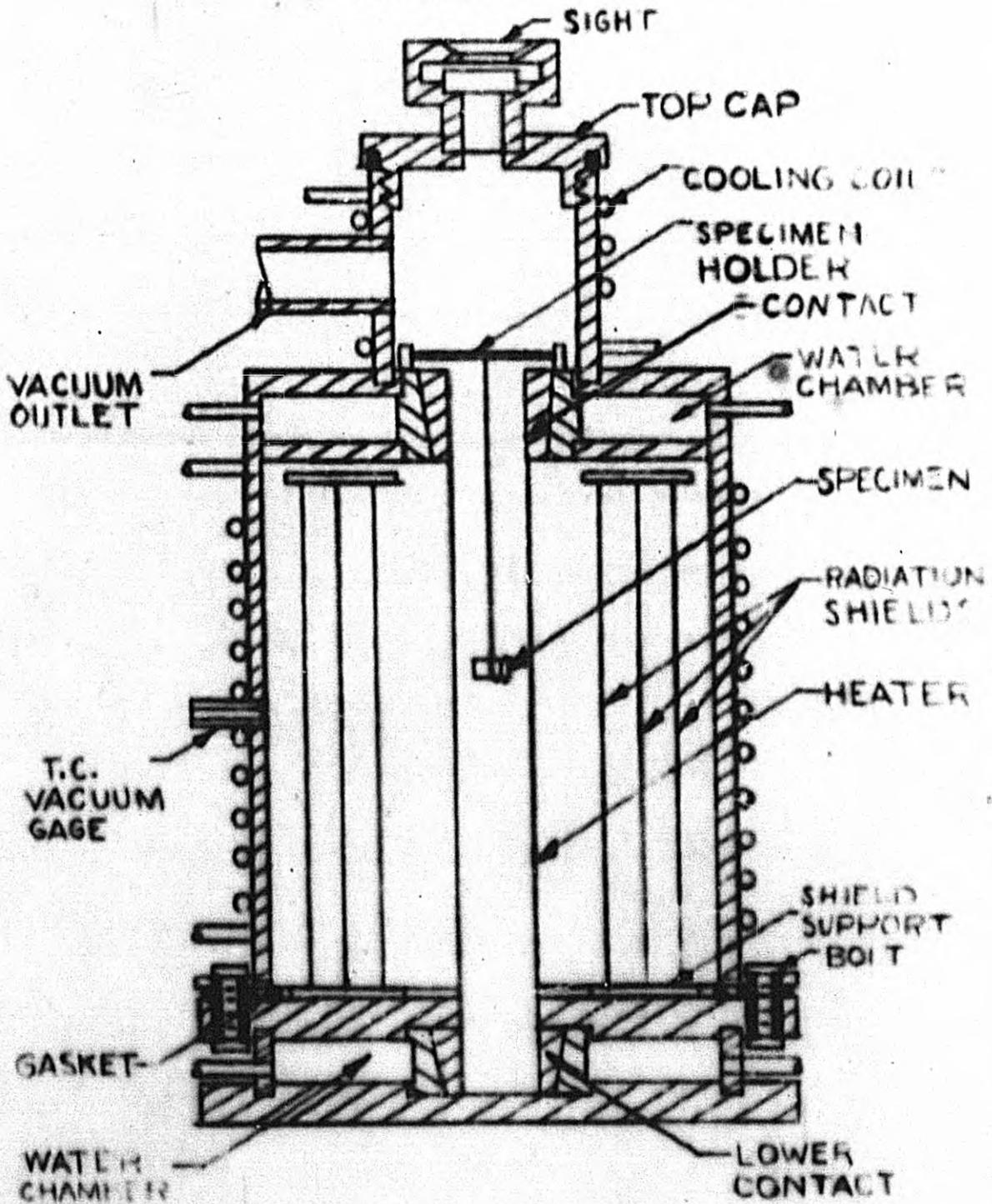


Figure 14 - Diagram of the Vacuum Furnace

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3. Extrusion

The extrusion apparatus used is illustrated in Figure 15. All extrusions were jacketed in either copper or steel tubing. In addition, several types of lead and cut-off plugs were explored. The billet diameter used in this extrusion work was 5/8 inch. Reduction ratios of 2:1 and 2.46:1 were tried at temperatures of 760°C and 840°C. Punch pressures ranged from 49 tons to 104 tons per square inch.

4. Hot Rolling

Hot rolling of jacketed UC and Sircaloy II powders was examined as a compacting method. Figure 16 shows the type of rolling billet used in these experiments. Conical end plugs were provided in order to avoid the formation of a steel core inside the rolled cermet.

The blended powder charge or previously compacted cermet was placed in the jacket after one end had been welded. Following this, the opposite end plug was inserted but not welded. Before final welding, the billet was evacuated to 0.1 μ pressure and high purity helium was readmitted. Evacuation and purging was repeated three times. The final weld was made after the third purging.

Hot working was carried out at temperatures between 800°C and 820°C. Initially, the billets were press forged from 1 inch diameter rounds to 1/2 inch thick flats. The billets were then rolled; reductions of 10 per cent per pass being taken. Rolling was continued until a total reduction in area of 90 per cent had been produced. This resulted in a jacketed cermet having overall dimensions of 6.3 inches x 1.58 inch x 0.25 inch.

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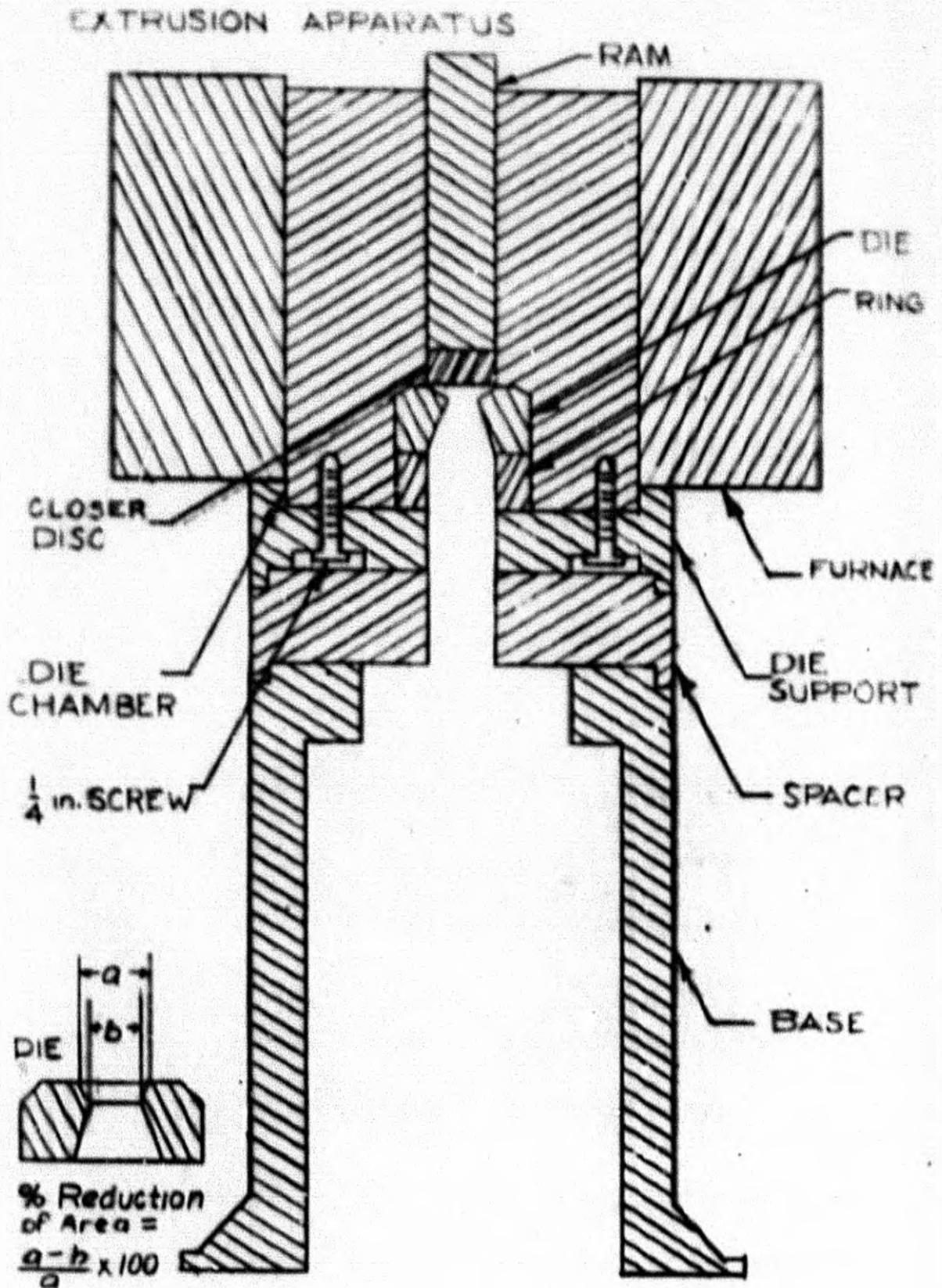


Figure 15 - Diagram of the Extrusion Apparatus

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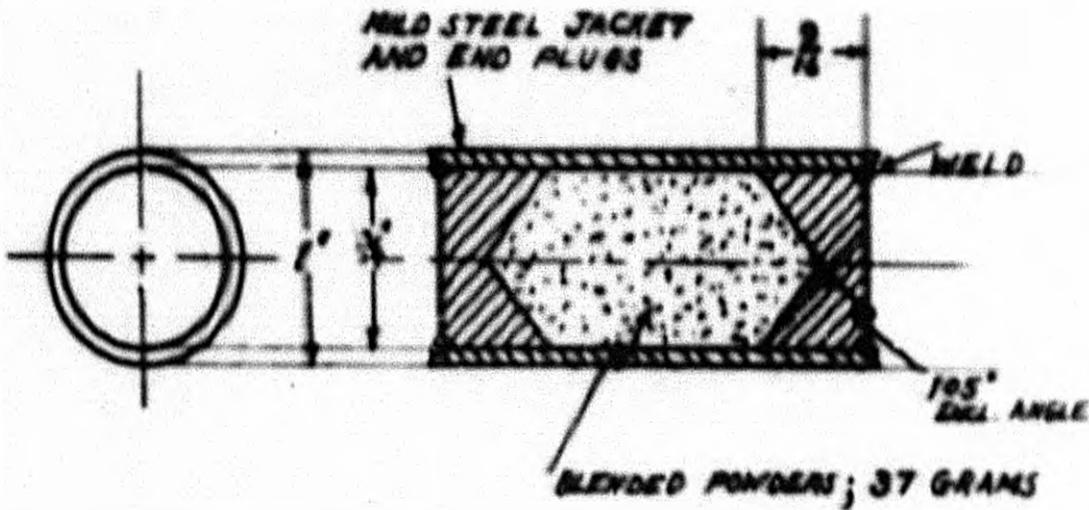


Figure 16

Rolling Mill

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III. EXPERIMENTAL RESULTS

A. Hot Pressing

Uranium monocarbide-Eircaloy II ceramets were prepared by hot pressing at temperatures from 900°C to 1400°C. It was found that full density could be attained at a temperature of 1200°C, using 6,000 psi punch pressure for compositions having up to 50 weight per cent UC. In all instances, pressure was maintained only for a maximum of 1 to 2 minutes. Compositions greater than 50 per cent UC were not investigated fully. Diffusion between uranium monocarbide particles and the Eircaloy II matrix proceeded rapidly at temperatures above 1000°C. However, a hot pressing temperature of at least 1100°C was required to produce fully dense ceramets. Thus, some composition change of the Eircaloy matrix occurred as a result of diffusion.

The extent of diffusion with increasing hot pressing temperatures may be seen in Figures 17, 18, 19, and 20. The interface between uranium monocarbide particles and the Eircaloy II matrix is shown as diffusion proceeds with increasing temperature. The powder materials used to form these specimens had the following impurities:

Eircaloy II hydride powder - approximately 2.1 % H₂,
0.004 % O₂,
0.019 % N₂, and
C not detected.

Uranium Monocarbide Powder - 4.67% C, 70 ppm H₂,
0.37% O₂, and 0.019% N₂.

Experience has shown that Eircaloy II powder might be expected to pick up about 0.01% carbon during hot pressing.

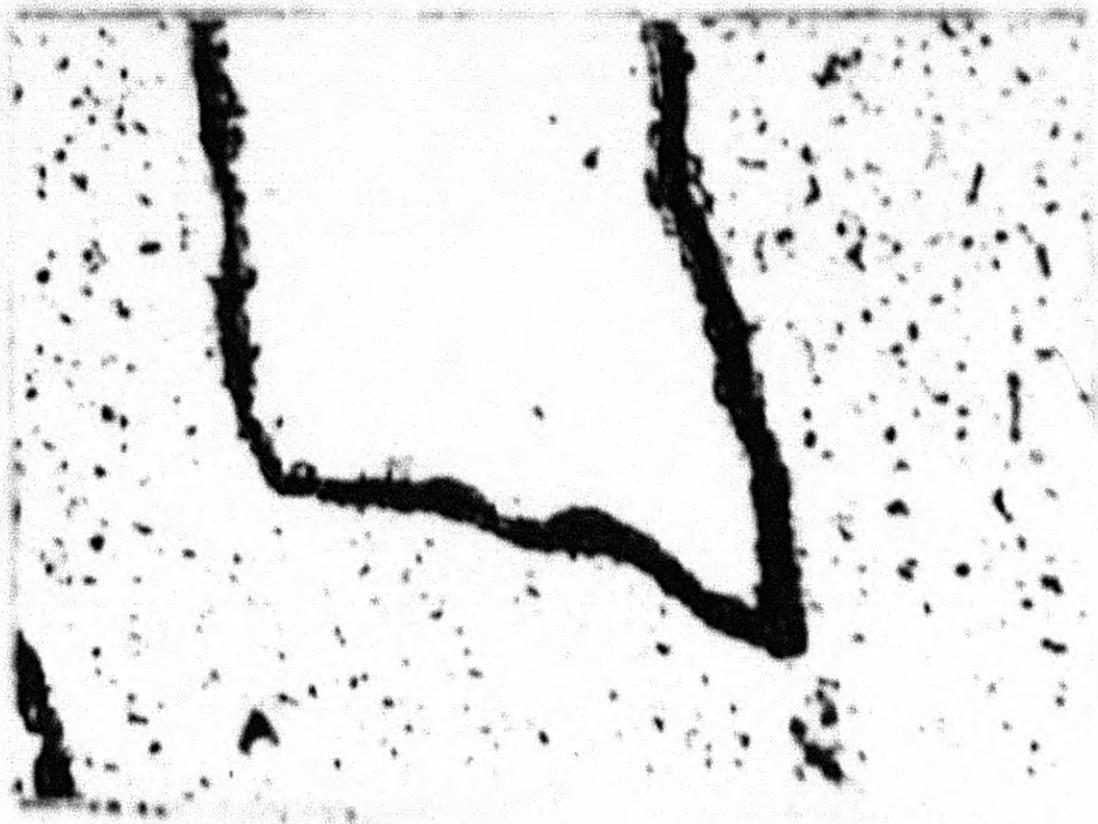


Figure 17

Negative Number 1144

Mag. 150 X diameter

Etchant: Electrolytic polish,
HF + HNO₃, Etch

Materials: Single uranium monocarbide particle surrounded by diffusion zone,
hot pressed at 1100°C. Average width of transformed diffusion zone
 4.7×10^{-6} inch.

Comment: The uranium monocarbide is seen as the light clear area enclosed by
the dark etching zone. The dark points in the electrolytic etch matrix
are believed to be etching pits.



Figure 18

Negative Number 11165
Etchant: Electrolytic polish
HF + HNO₃ etch

Mag. 250 X diameter

Material: Diffusion zone surrounding uranium monocarbide in cermet hot pressed at 1200°C. Average width of transformed diffusion zone 8.0×10^{-4} inch.

Comments: The uranium monocarbide is seen as the light clear area enclosed by the dark etching zone. The dark points in the Uralloy II matrix are believed to be etching pits. The diffusion zone is increasing.

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Figure 19

Negative Number 11463

Mag. 250 X diameter

Etchant: Electrolytic polish
HF + HNO₃, etch

Material: Diffusion zones in cermet specimen hot pressed at 1300°C. Average width of transformed diffusion zone 2.2×10^{-3} inch.

Comment: The uranium monocarbide is seen as the light clear area enclosed by the dark etching zone. The dark points in the Eirealoy II matrix are believed to be etching pits. Eirealoy II is at the lower left.

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Figure 20

Negative Number 11466
Etchants: Electrolytic polish
HF + HNO₃ etch

Mag. 250 X diameter

Material: Diffusion zones in cermet specimen hot pressed at 1200°C. Average width of transformed diffusion zone 3.1×10^{-3} inch.

Comment: Uranium monocarbide is the light clear area. Etch pits and acicular structure appear in the remaining matrix. Many carbide particles have become connected by continuous transformed diffusion zones.

Tables VII, VIII, IX, and I list the performance of hot pressed specimens for which corrosion testing was completed. Specimens numbers 10, 50, 60, 10, and 20; containing 20 per cent by weight UC (10-12 mesh) (Table VII), were the only compositions that withstood 600°F water corrosion tests for any significant length of time. The appearance of corrosion tested hot pressed cermet specimens is illustrated in Figures 21, 22, and 23. Table XI describes warm pressed cermets that were made. It was found that the same type of laminations appeared in these bodies as did in the cold pressed and sintered bodies.

B. Cold Pressing and Sintering

Only a limited number of cold pressed and sintered cermet specimens were prepared. The cermet specimens prepared by this method were laminated in the green (as pressed) condition before sintering. Furthermore laminations increased during sintering. Data for these specimens are listed in Table III. A more extensive investigation of die wall lubricants and height-diameter ratios might aid in overcoming this problem. However, it is now known that diffusion between uranium monocarbide and Hircaloy II occurs extensively at the lowest sintering temperature required to approach full density, even for pure zirconium. According to Elish, Hausner, and Angier⁵ six hours sintering time at 1050°C using a compacting pressure of 75 psi would be required. In view of these data, only minor emphasis was placed upon the preparation of cermets by cold pressing and sintering.

⁵Ibid.

TABLE VII

Performance of 30% UO₂-Zirconium II Hot Pressed Ceramite

Theoretical Density 7.65 gm/cm³

Specimen Number	Preparation	Density gram/cc	Corrosion Performance	
			Weight Loss Boiling Water Atmosphere Pressure mg/cm ²	Weight Loss 500°F Water mg/cm ²
6 C	- 16 + 32 mesh UC saw filing Zr II powder, hot pressed 900°C	7.36	-	75 hours disintegrated
1 C	- 16 + 32 mesh UC saw filing Zr II powder, hot pressed 1000°C	7.59	-	46.7 148 hours
5 C	- 16 + 32 mesh UC saw filing Zr II powder, hot pressed 1050°C	7.53	-	6.06 148 hours
4 C	- 16 + 32 mesh UC saw filing Zr II powder, hot pressed 1100°C	7.47	-	1.82 148 hours
3 C	- 16 + 32 mesh UC saw filing Zr II powder, hot pressed 1200°C	7.50	-	2.79 148 hours
2 C	- 16 + 32 mesh UC saw filing Zr II powder, hot pressed 1300°C	7.56	-	16.8 148 hours

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Table 121 - Continued

Specimen Number	Preparation	Density grams/cm ³	Corrosion Performance	
			Weight Loss Atmosphere mg/cm ²	Weight Loss Dist. Water mg/cm ²
7 F	- 16 + 80 mesh UC powder, hot pressed 1200°C see filing & II	8.1	122.0 8 hours	
8 VF	- 80 mesh and down UC powder, hot pressed 1200°C see filing & II	7.57	9.73 8 hours	
10 VF	- 80 mesh and down UC powder, hot pressed 1200°C see filing & II	7.07	-	
9 VF	- 80 mesh and down UC iodide Irovanium see filing powder	7.37	27.6 8 hours	

* All hot pressing 1 minute at temperature.

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ATOMIC ENERGY ACT-1954**TABLE VIII****Performance of 40% UC-Zircaloy II Hot Pressed Ceramets***Theoretical Density 8.08 gm/cm³

Specimen Number	Preparation	Density gram/cc	Corrosion Performance
			Weight Loss Boiling Water Atmosphere Pressure mg/cm ²
1	- 16 + 80 mesh UC - 100 mesh Zr II hydride powder, hot pressed 1100°C	-	16 hours disintegrated
3	- 16 + 80 mesh UC - 100 mesh Zr II hydride powder, hot pressed 1100°C	7.85	2 1/2 hours disintegrated
4	- 16 + 80 mesh UC - 100 mesh Zr II hydride powder, hot pressed 1100°C	7.90	-
10	- 16 + 32 mesh UC Zr II saw filing powder	8.12	147.0 8 hours

* Hot pressed 1 minute at temperature.

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TABLE II**Performance of 90% UC-Zircaloy II Hot Pressed Carbots***Theoretical Density 8.99 gm/cm³

Specimen Number	Preparation	Density gm/cm ³	Corrosion Performance
			Weight Loss Boiling Water Atmosphere Pressure gm/cm ²
23	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 925°C	8.47	4 hours disintegrated
24	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 925°C	8.52	4 hours 210
25	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 925°C	8.60	4 hours 143
26	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1000°C	8.33	4 hours disintegrated
19	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1050°C	8.70	8 hours disintegrated
27	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1075°C	8.40	4 1/2 hours disintegrated
1	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1100°C	7.70	1 1/2 hours disintegrated
2	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1100°C	7.90	10 hours disintegrated
4	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1100°C	8.15	24 hours disintegrated

* Hot pressed 1 minute at temperature.

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Table IX - Continued

Specimen Number	Preparation	Density gm/cm ³	Corrosion Performance
			Weight Loss Boiling Water Atmosphere Pressure mg/cm ²
14	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1100°C	8.80	8 hours disintegrated
29	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1200°C	8.66	4 1/2 hours disintegrated
13	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1200°C	8.98	20 hours disintegrated
30	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1200°C	-	4 hours 637
21	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1210°C	8.90	12 hours disintegrated
15	- 16 + 80 mesh UC, -100 mesh Zircaloy II hydride powder, hot pressed 1300°C	8.85	8 hours disintegrated
51	- 16 + 80 mesh UC, 2r II saw filing powder, hot pressed 950°C	8.40	8 hours 770
49	- 16 + 80 mesh UC, 2r II saw filing powder, hot pressed 1000°C	8.44	4 hours 590
46	- 16 + 80 mesh UC, 2r II saw filing powder, hot pressed 1050°C	8.65	4 hours 354
43	- 16 + 80 mesh UC, 2r II saw filing powder, hot pressed 1100°C	8.91	4 hours 590

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Table II - Continued

Specimen Number	Preparation	Density gm/cm ³	Corrosion Performance
			Weight Loss Boiling Water Atmosphere Pressure mg/cm ²
41	- 16 + 80 mesh UC, Zr II saw filling powder, hot pressed 1200°C	8.87	4 hours 512
39	- 16 + 80 mesh UC, Zr II saw filling powder, hot pressed 1300°C	8.92	-
58	50 wt % (- 16 + 32) UC, 50 wt % Zr II saw filings, hot pressed 1200°C	8.60	4 hours disintegrated
59	50 wt % (- 16 + 32 mesh) UC, 48.5 wt % Iodide Zr, 1.5 wt % Sn, hot pressed 1200°C	8.53	4 hours disintegrated
60	50 wt % (- 16 + 32 mesh) UC, 40 wt % Zr II, 10 wt % Sn, hot pressed 1200°C	8.95	4 hours disintegrated
61	50 wt % UC (-80 mesh), 50 wt % Zr II saw filings, hot pressed 1200°C	8.75	-

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ATOMIC ENERGY ACT**TABLE I****Performance of 60% UC-Zircaloy II Hot Pressed Ceramets***Theoretical Density 9.24 g/cm³

Specimen Number	Preparation	Density g/cm ³	Corrosion Performance
			Weight Loss Boiling Water Atmosphere Pressure mg/cm ²
H ₂ O Zr 1	60 wt % (- 16 + 80 mesh) UC, - 100 mesh Zr II, hot pressed 1100°C	9.3	2 1/2 hours disintegrated
H ₂ O Zr 2	60 wt % (- 16 + 80 mesh) UC, - 100 mesh Zr II, hot pressed 1100°C	9.0	-
H ₂ O Zr 3	60 wt % (- 16 + 80 mesh) UC, - 100 mesh Zr II, hot pressed 1100°C	9.3	-
H ₂ O Zr 1F	60 wt % (-80 mesh) UC, -100 mesh Zr II, hot pressed 1100°C	8.85	-
H ₂ O Zr 2F	60 wt % (-80 mesh) UC, -100 mesh Zr II, hot pressed 1100°C	-	-
H ₂ O Zr 3F	60 wt % (-80 mesh) UC, -100 mesh Zr II, hot pressed 1100°C	-	-

* Hot pressed 1 minute at temperature.

** Zr II hydride powder.

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Figure 21

Negative Number 12176

Mag. 3 X diameter

Hot Pressed 30% UC Cermet After Autoclave Corrosion Test

Material: 30 weight per cent UC, 70 weight per cent Zircaloy II cermet
(-16 + 32 mesh UC), hot pressed 1050°C, held in water at 600°F for
148 hours. (Specimen 1C, Table 1)

Comments: Corrosive attack did not proceed beyond surface carbides.

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Figure 22

Negative Number 12173

Mag. 3 diameter

Hot Pressed UC Cermet After Autoclave Corrosion Test

Material: 30 weight per cent UC, 70 weight per cent Sircaloy II cermet (-16+32 mesh UC), Specimen 20, Table IX. Hot pressed 1300°C, held in water at 680°F for 148 hours.

Comment: This specimen, hot pressed at 1300°C, was attacked more extensively than the specimen shown in Figure 21 which was hot pressed at 1050°C.

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Figure 2)

Negative Number 1238)

Mag.) X diameter

Hot Pressed 50 Weight Per Cent UC Cermet After Boiling Water Corrosion Test

Materials: 50 weight per cent UC, 50 weight per cent Eircaloy II cermet (16 + 32 mesh UC), hot pressed 1200°C, tested in boiling water 8 hours (atmospheric pressure).

Comment: The corrosive attack during the boiling water test penetrated beyond the surface carbides resulting in the fissures through the body.

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TABLE II

Performance of 50% UC-Zircaloy II Warm Pressed Cornets*

Theoretical Density 8.59 gm/cm³

Specimen Number	Preparation	Density gm/cm ³	Corrosion Performance
			Weight Loss Boiling Water Atmosphere Pressure mg/cm ²
W50 Zr-1C	50 wt % (-16 + 32 mesh) UC, Zr II saw filing powder, warm pressed 650°C, 25 TSI in carbon mold using a tool steel punch, laminations noted in specimen	-	-
W50 Zr-2C	50 wt % (-16+32 mesh) UC, Zr II saw filing powder, warm pressed 650°C, 25 TSI in carbon mold using a tool steel punch, laminations noted in specimen	-	-
W50 Zr-3C	50 wt % (-16+32 mesh) UC, Zr II saw filing powder, warm pressed 650°C, 25 TSI in carbon mold using a tool steel punch, laminations noted in specimen	8.47	-
W50 Zr-4C	50 wt % (-16 +32 mesh) UC, Zr II saw filing powder, warm pressed 650°C, 50 TSI in steel die with carbon liner	-	4 hours laminations appeared
W50 Zr-5C	50 wt % (-16 + 32 mesh) UC, Zr II saw filing powder, warm pressed 650°C, 50 TSI in steel die with carbon liner	8.27	2 1/2 hours 296

* Warm pressed generally 1 minute at temperature.

TABLE XII

Performance of Cold Pressed and Sintered UC-Zircaloy II Ceramets*

Specimen Number	Preparation	Sintered Density	Corrosion Performance
			Weight Loss Boiling Water Atmosphere Pressure mg/cm ²
C 50 Zr-4C	50 wt % UC (-16- 80 mesh), 50 wt % -100 mesh Zr II hydride powder, cold pressed 75 TSI, no lubricant, sintered one hour 1150°C, theoretical density 8.59 gm/cm ³	laminations present, estimated as 6.5 gm/cm ³	4 hours disintegrated
C 50 Zr-5C	50 wt % UC (-16- 80 mesh), 50 wt % -100 mesh Zr II hydride powder, cold pressed 75 TSI, no lubricant, sintered one hour 1150°C, theoretical density 8.59 gm/cm ³	laminations present, estimated as 6.5 gm/cm ³	4 hours 43.8
C 90 Zr-1C	10 wt % UC (-16- 80 mesh), 50 wt % -100 mesh Zr II hydride powder, cold pressed 90 TSI, no lubricant, sintered one hour 1150°C, theoretical density 6.88 gm/cm ³	laminations present, estimated as 5.2 gm/cm ³	4 hours disintegrated

* A total of 12 cold pressed and sintered ceramets were prepared. Only three were sufficiently free of laminations for corrosion testing.

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C. Extrusion

Data for the extruded uranium monocarbide-Zircaloy II cermet which were made and corrosion tested, are listed in Table XIII. Full density was not reached in the extrusions prepared from non-compacted powders. This is in part related to the small size of the extrusion apparatus. With a 5/8 inch diameter extrusion chamber there is some doubt that the proper billet temperature was retained during extrusion. However, these experiments have served to demonstrate that uranium monocarbide-Zircaloy II cermets could be formed by extrusion. With larger equipment, it is likely that fully dense cermet specimens could be formed at temperatures sufficiently low to avoid rapid diffusion between UC and Zircaloy II. Experimental extrusions are illustrated in Figures 24, 25, and 26.

D. Hot Rolling

Data for hot rolled uranium monocarbide-Zircaloy II cermets are listed in Table XIV. The hot rolled cermets have shown promise in that densities from 92.5 to 96.0 per cent theoretical have been obtained with very little accompanying diffusion. This is illustrated in Figures 27 and 28. The microstructure of the interface between a single uranium monocarbide particle and the Zircaloy II matrix as observed in specimens numbers 1 and 3 (Table XIV) are shown.

Although the hot rolled cermet specimens did not show adequate corrosion resistance, the elimination of diffusion is considered to be an important step toward its attainment. Further development of

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TABLE XIII

Performance of Uranium Monocarbide-Zircaloy II Extruded Rods

Theoretical Density 8.59 gm/cm³

Specimen Number	Preparation	Density gm/cm ³	Corrosion Performance
			Weight Loss Boiling Water Atmosphere (Pressure mg/cm ²)
3	50 wt % (-16 +32 mesh) UC, 50 wt % Zr II saw filings, hot pressed 1200°C copper jacketed for extrusion, reduction of area 75%, extrusion temperature 760°C	7.225	All carbides leached out after 6 hours in boiling water followed by 168 hrs in 680°F water
4	100% Zr II powder, copper jacketed for extrusion, reduction of area 75%, extrusion temperature 760°C	6.609	-
13	50 wt % (-80 mesh) UC, 50 wt % Zr II saw filings, not compacted, SAE 1020 steel jacket, reduction of area 75%, extrusion temperature 840°C	3.923	4 hours 226
14	50 wt % (-80 mesh) UC, 50 wt % Zr II saw filings, not compacted, SAE 1020 steel jacket, reduction of area 75%, extrusion temperature 840°C	4.950	4 hours 289
16	50 wt % (-80 mesh) UC, 50 wt % Zr II saw filings, not compacted, SAE 1020 steel jacket, reduction of area 75%, extrusion temperature 840°C	3.919	4 hours 236

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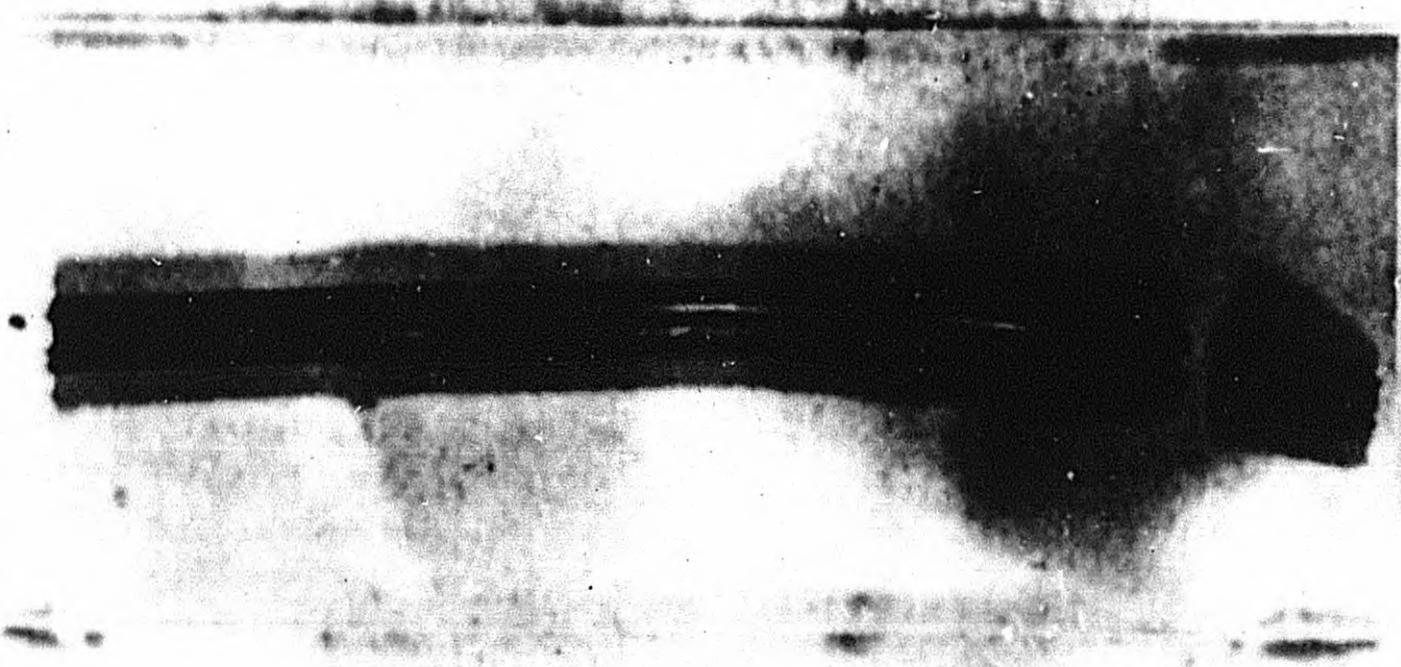


Figure 2h

Negative Number 12103

Mag. 1.5 X diameter

Uranium Monocarbide-Zircaloy II Cermet As Extruded with Copper Sheath In Place

Material: Extrusion No. 3, copper jacketed hot pressed cermet, 50 weight per cent U (-16.32 mesh), balance Zircaloy IX, hot pressed 1200°C followed by extrusion at 760°C (Specimen No. 3, Table VII).

Comments: Following extrusion, the copper jacket was removed with concentrated HNO_3 and the extruded cermet was corrosion tested. As shown above, the copper lead plug is to the right and the carbon plug is inside the jacket on the left.

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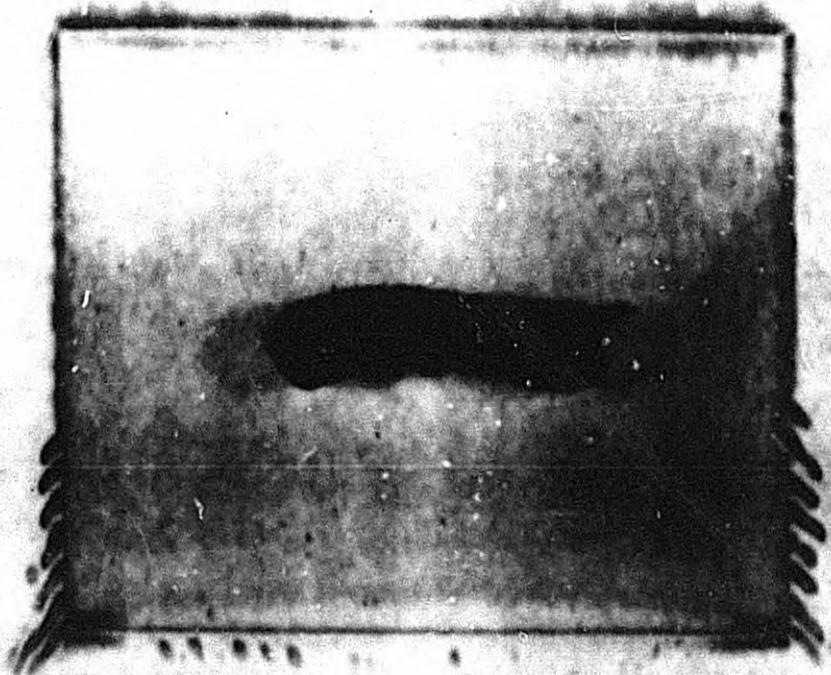


Figure 25

Negative Number 13187

Mag. 1.5 X diameter

Uranium Monocarbide-Sircaloy II Cermet After Boiling Water Corrosion Test

Material: Extrusion No. 3, copper jacketed hot pressed cermet, 90 weight per cent UC (-16+32 mesh), balance Sircaloy II, hot pressed 1200°C followed by extrusion at 760°C (Specimen No. 3, Table VII).

Comments: The specimen is shown after removal of the copper jacket with concentrated HNO₃ and 8 hours exposure to boiling water. The weight loss indicated about 60 per cent of the contained uranium monocarbide had been corroded away after this test.

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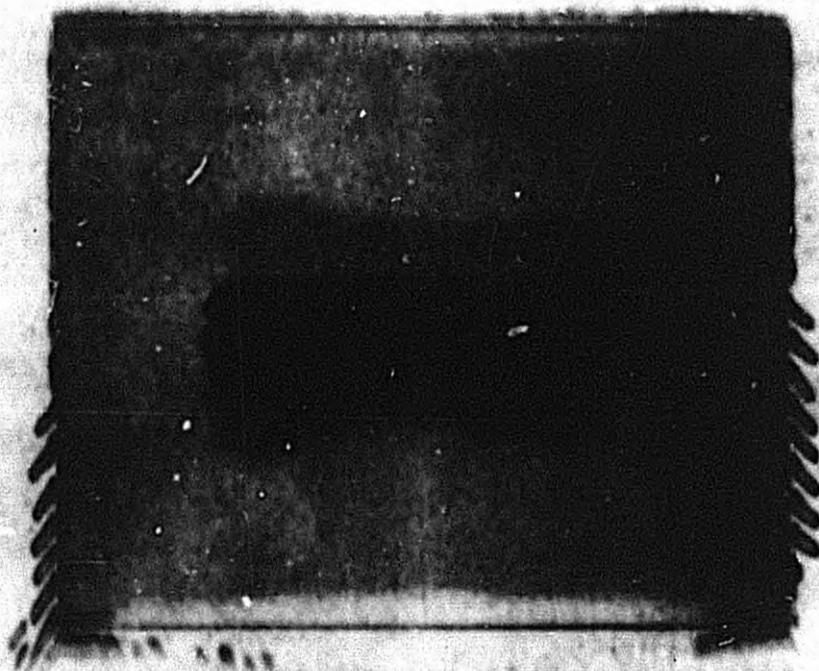


Figure 26

Negative Number 12788

Mag. 1.5 X diameter

Uranium Monocarbide-Sircaloy II Cermet After 680°F Water Corrosion Test

Material: Extrusion No. 3, copper jacketed hot pressed cermet, 50 weight per cent UC (-16 + 32 mesh), balance Sircaloy II, hot pressed 1200°C followed by extrusion at 760°C (Specimen No. 3, Table VII).

Comment: Following the boiling water corrosion test, the specimen was held 148 hours in 680°F water and then sectioned for examination. It was found that no carbide particles remained in the interior of the extrusion.

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ATOMIC ENERGY ACT-1954TABLE XIVPerformance of Hot Rolled 50% UC-Zircaloy II CermetTheoretical Density 8.99 gm/cm³

Specimen Number	Preparation	Density gm/cm ³	Corrosion Performance	
			Weight Loss Boiling Water Atmosphere Pressure mg/cm ²	
1	Steel jacketed non-compacted powders, UC -100+ 200 mesh, Zircaloy II saw filings, press forged and rolled at 816°C	8.06	4 hours	1004
2	Steel jacketed non-compacted powders, UC -200 mesh, Zr II saw filings, press forged and rolled at 816°C	8.17	4 hours	1033
3	Steel jacketed cermet, previously hot pressed 1200°C before being jacketed for rolling, UC powder -16+ 18 mesh, Zr II saw filings powder, press forged and rolled at 816°C	8.57	8 hours	438
5	Steel jacketed cermet, previously warm pressed 820°C, UC powder -16+ 18 mesh, Zr II saw filing powder, press forged and hot rolled at 816°C	7.93	-	-
6	Steel jacketed cermet, previously warm pressed 820°C, UC powder -16+ 18 mesh, Zr II saw filing powder, press forged and hot rolled at 816°C	8.22	8 hours	491
8	Steel jacketed non-compacted powders, -16+ 18 mesh UC, Zr II saw filing powder, press forged and hot rolled at 816°C	8.26	8 hours	437

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Figure 27

Negative Number LJE
Etchant: Chromic Acid

Mag. 1000 X diameter

Interface Between UO₂ Particle and
Zircaloy II Matrix in Hot Rolled Cermet

Materials: Specimen No. 1, Table XIV. 50 weight per cent UO₂, -100 + 200 mesh, balanced with Zircaloy II saw filings, steel jacketed, press forged and rolled at 800. 871°C.

Comment: No transverse diffusion zone between the two phases could be seen at 1000 diameters magnification.

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Figure 28

Negative Number 12316
Etchant: Chromic Acid

Mag. 1000 X diameter

Interface Between UC Particle and Zircaloy II Matrix
in Hot Pressed Cermet Which Was Subsequently Hot Rolled

Material: Specimen No. 3, Table IIV. 50 weight per cent UC (-16-18 mesh),
balance Zircaloy II cermet. Initially hot pressed 1200°C, then
jacketed, press forged and rolled at 816°C.

Comments: Diffusion occurred during hot pressing. The extent of diffusion
is indicated by the white band between the two phases.

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this technique, in the direction of attaining 100 per cent densification and improved dispersion of UC, might very well give a positive result.

IV. DISCUSSION

Comparison of corrosion performance of cermets made by techniques such as hot pressing, cold pressing and sintering, extrusion, and hot rolling show that the 30 weight per cent carbide cermet made by hot pressing was the highest composition that resisted corrosion in 680°F water. In addition, it has been found that the same composition hot pressed under the same conditions, but having carbide finer than 100 mesh, was not corrosion resistant. This highlights the fact that the corrosion performance of UC-Zircaloy II cermets was strongly influenced by the separating distance between UC particles in the Zircaloy II matrix. By the techniques used, this separation should be on the order of 650 microns. A larger average particle size results in larger separating distances between the dispersed UC particles.

Cermets prepared by the hot pressing process have all shown diffusion zones surrounding the carbide particles. For example, diffusion zones in hot pressings made at 1200°C might add as much as 20 per cent to the measured diameter of the uranium monocarbide particles in the Zircaloy II matrix. Direct observation of the corrosion process has shown that diffusion zones are attacked at almost the same rate as are the UC particles.

These data indicate that corrosion performance would be improved if diffusion zones are reduced to a minimum. Diffusion zones have been minimized in cermets made by extrusion and hot rolling. However, full densification was not reached in the cermets prepared by these methods and

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thus a reliable comparison with hot pressings cannot be made.

In comparison, the sintering temperatures required for the preparation of cermets by cold pressing and sintering are now known to be sufficiently high to cause rapid diffusion. This difficulty, combined with the tendency for cold pressed cermets to laminate, indicates the cold pressing and sintering process to be the least favorable of those investigated.

V. RECOMMENDATIONS

Uranium monocarbide can be prepared by arc melting to meet the stoichiometric composition.

The corrosion resistance of the 30 weight per cent uranium monocarbide-Zircaloy II cermet composition indicates that the production of cermets up to this composition is feasible. Cermets of this composition, at present, require a particle size range of approximately 0.021 to 0.015 inch average diameter for the dispersed uranium monocarbide. This applies only to fully dense cermets hot pressed at 1200°C and is necessary in order to have sufficient interparticle separation to limit corrosive attack to the surface carbides.

In addition to the 30 weight per cent composition of demonstrated corrosion resistance, encouraging steps have been made toward the development of compaction processes that minimize diffusion between uranium monocarbide and Zircaloy II. The most promising of these is the hot rolling process. Further development of this process would require the attainment of full density at temperatures below 820°C and exploration of means to maintain uniform dispersions of UC during hot rolling.

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Another compaction method which might offer promise for carbide additions below 30 per cent is the pressure sintering technique. Pressure sintering has not been explored during the current program. However, this technique has been used successfully to compact beryllium and titanium powders. For exploration of this technique, apparatus would be required that would allow the blended UC and Zircaloy II powders to be confined under pressures on the order of 1000 psi in vacuum for eight or more hours. There is little doubt that uniform dispersions could be attained this way. However, the relation between pressure sintering temperatures (up to 1000°C) and the diffusion that might occur between the two phases is at present unknown.

In summary, the following procedures are recommended as being most feasible for the further development of uranium monocarbide-Zircaloy II cermets:

1. Corrosion resistant cermet containing 30 weight per cent of -16 + 32 mesh UC can be made by hot pressing.
2. The hot rolling process offers a means to fabricate cermets having a minimum of diffusion between the two phases. Further development is necessary to attain full density and uniform dispersion of uranium monocarbide. If the development of this technique were fully successful, it could be utilized for the manufacture of cermets containing up to 30 weight per cent UC but having more finely divided UC particles than is now possible. Should this improved technique lead to the development of corrosion resistant 30 weight per cent cermets having more finely divided UC, the possibility of higher composition cermets compatible with a given particle size UC would be indicated.

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3. Pressure sintering might offer the same advantages as hot rolling.
4. For the additional development of any of these techniques, more effort should be directed toward control of particles size and shape for both the uranium monocarbide and Zircaloy II powders. In addition, an independent study of the effects of UC corrosion products on the corrosion resistance of Zircaloy II would be helpful in advancing this development.

VI. LOGBOOKS

Data relating to the work reported herein are recorded in AUF Logbooks C-4871, C-4862, C-4876, C-5032, C-5148, C-5151, C-5157, C-5297, C-5300, C-5416, C-5417, C-5418, C-5461, C-5462, C-5463, and C-5464.

VII. CONTRIBUTING PERSONNEL

The following Foundation personnel were the major contributors to the work:

R. Fore	- Research Technician
H. Friedman	- Assistant Metallurgist
R. L. Hodson	- Research Technician
D. M. Jacobson	- Research Technician
E. Koehler	- Research Metallurgist
T. L. Marion	- Research Technician
S. W. McGee	- Associate Metallurgist
H. R. Nichols	- Assistant Metallurgist
R. H. Read	- Research Metallurgist
C. H. Sump	- Supervisor, Powder Metallurgy
T. S. Tully	- Research Technician
R. J. Van Thynne	- Assist. Supervisor, Reactor Metallurgy

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Mr. R. J. Van Thyne developed the arc melting technique for uranium monocarbide and the arc melted material was prepared under his supervision.

Respectfully submitted,

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