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**LAYER FORMATION BY INTERDIFFUSION
BETWEEN SOME REACTOR CONSTRUCTION
METALS**

By
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June 17, 1949

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LAYER FORMATION BY INTERDIFFUSION BETWEEN
SOME REACTOR CONSTRUCTION METALS

J. Howard Kittel

METALLURGY DIVISION

June 17, 1949

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under
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LAYER FORMATION BY INTERDIFFUSION BETWEEN SOME REACTOR CONSTRUCTION METALS

J. Howard Kittel

INTRODUCTION

The present design of the Experimental Breeder Reactor calls for numerous metal-to-metal contacts. Additional contacts may result because of dimensional changes or warping of the fuel elements after the pile has been operated for a length of time. The metal-to-metal contacts will generally occur under reducing conditions so that the contacting surfaces will be quite clean and usually free of oxide films. The presence of such conditions, along with the elevated temperatures associated with normal operation of the reactor, makes it likely that many of the metal-to-metal contacts will in effect act as diffusion couples, i.e., continuous interpenetration of two adjoining metals may occur.

The possible existence of diffusion couples in the reactor is a matter of some importance for two reasons: (a) the possibility of radioactive or other undesirable elements reaching the coolant stream with attendant contamination of pumps, heat exchangers, etc.; and (b) the formation of solid bonds or welds which might make difficult the removal of fuel rods and other metal parts.

The reactor components which normally will be in contact in the hottest part of the pile are the following:

1. Fuel rods and fuel rod spacers.
2. Fuel rod jackets and fuel rod spacers.

In addition, the following components may be in contact, should warping of dimensional changes occur in the assembled fuel elements:

1. Fuel rods and fuel rod jackets.
2. Fuel rod jackets (one with another).
3. Fuel rod jackets and separating plates.
4. Fuel rod jackets and plate into which the lower end of the assembled fuel rod is inserted.

The tendency towards dimensional instability which uranium exhibits when subjected to repeated heating cycles presents the possibility that the assembled fuel rods will deform to some extent during the anticipated normal use of the reactor.

In order to study the diffusion reaction characteristics of the metals which have been proposed for use in the pile, a number of experiments have been completed in which many combinations of the proposed metals have been given diffusion treatments at various elevated temperatures for extended lengths of time. The metals being studied are beryllium, columbium, iron, molybdenum, nickel, tantalum, titanium, uranium, tungsten, zirconium, and 347 stainless steel. The above metals have all been used in a commercially pure state.

The experimental temperatures ranged from 400° to 800°C., and the durations of the diffusion treatments ranged from 6 to 48 days. With the exception of titanium, over 400 diffusion couples representing all possible combinations of the above eleven metals have been made and examined after diffusion anneals. Titanium was not on hand during most of the investigation, and at the time of writing it has been tested only against uranium and 347 stainless steel at 500°C.

A series of tests was also made to evaluate the strengths of the bonds formed when interdiffusion of the metals occurred.

APPARATUS AND PROCEDURE

Rates of Layer Formation

The initial requirement for specimens which are required to provide reliable data on the interdiffusion of metals is that flawless contact be established between uncontaminated surfaces of the metals to be studied. With this requirement in mind, as well as the consideration that a large number of diffusion couples would be needed for the investigation, diffusion specimens in a holder shown assembled in Figure 1 were used in the experiments.

Essentially, the specimens were small sheets of material compressed together in a plastically deformed container. The specimens themselves measured $3/8"$ x $3/4"$ and varied in thickness from 0.055" to $1/8"$. Each surface of each specimen which was to contact another specimen was metallographically polished through 3/0 emery paper, with the final polish always being in the direction of the longer dimension of the specimen. In order to prevent oxide contamination of the surfaces of the uranium specimens, which occurred within a few minutes after emery polishing, they were electro-polished after the final polish on emery paper. A series of tests made with freshly emery-polished uranium specimens and electro-polished specimens showed no differences in diffusion reaction rates.

The specimen holders were $3/4"$ long and were cut from $7/8"$ square cold-rolled 1020 steel bar stock. A $3/8"$ square hole was drilled through each specimen in the $3/4"$ direction. In this square hole from 4 to 8 specimens were placed, after which the assembled specimens and holder were

compressed under 70,000 pounds in a direction normal to the polished surfaces of the specimens. The compression load was sufficient to plastically deform the holder and, to some extent, the specimens themselves, depending upon their hardness. This procedure was found to be not only simple and rapid, but yielded the required perfect contact between the diffusion metals in all but about 1% of the tests. A further advantage was that each assembled holder contained up to 7 diffusion interfaces, a factor which greatly shortened the metallographic work involved in the microexaminations after the tests.

For diffusion treatments, groups of the assembled specimens were annealed in evacuated stainless steel containers in which was placed sufficient NaK alloy to completely cover the specimens. The NaK served as an efficient heat transfer medium and also minimized oxidation of the specimens. Each container, in which was constructed a well for a thermocouple, was heated in a vertical tube furnace. In most of the tests the variation from the desired temperature was less than ± 5 degrees. Occasionally fluctuations somewhat larger than this were encountered.

The only uncertainty as to the annealing time is that introduced by the period of heating and cooling, and errors from this source are believed to be less than two hours in all tests. This is about 1.5% error in the six-day tests and correspondingly less in the longer tests.

After a diffusion-anneal the assembled specimens were cut as shown in Figure 1 and metallographically polished for photomicrography of the diffusion interfaces. In many cases the balance of an assembled specimen, after removal of a section for metallography, was returned to the diffusion treatment and after further annealing again sectioned for metallographic examination. One assembled specimen, therefore, could provide three metallographic sections, each of which would have been annealed at the same temperature but for different lengths of time.

Most of the photomicrographs were made at a magnification of 250. If reaction layers were observed, their maximum total thickness was measured on the photomicrograph with a scale reading to $1/64$ ". This procedure provided a layer thickness measurement accuracy of $\pm 3 \times 10^{-5}$ inch. In uncertain cases photomicrographs at a higher magnification were made, with a correspondingly greater precision of layer thickness determination. Photomicrographs were made in areas believed to be representative of the entire specimen. In those cases where irregular layers were formed, the thickest portion of the layer observed in a visual microscopic examination was measured. Occasionally, therefore, thickness measurements appear in the data which are larger than indicated by the corresponding photomicrograph.

For each diffusion couple, many trials were made to find the etchant which would most clearly delineate the reaction layers. In some cases an unetched specimen was found to show the layers more clearly. Uranium

specimens were generally heated in air to oxidize reaction layers formed with the other metals.

Strengths of Diffusion Bonds

The first attempts to evaluate the strengths of the bonds were made with apparatus designed to force together, while submerged in NaK at the test temperature, the ends of cylinders made of the various metals. It was hoped that should bonding or welding occur, tensile specimens might be machined from the bonded metal. Difficulties were experienced in obtaining the contact required, so that specimens of the type shown in Figure 2 were used. The latter type of specimen provided shear stress data and was much simpler to use, for it was compressed and diffusion-annealed in the same specimen holder shown in Figure 1. The specimen shown in Figure 2 was tested in shear by imposing a tensile loading. A number of similar specimens were also used with short extended ends and were sheared by compression.

RESULTS AND DISCUSSION

Rates of Layer Formation

In many of the diffusion couples which were tested no reaction layers were noted. These combinations are listed in Table I. It will be noted that practically all of the couples which showed no evidence of reaction contain at least one of the high-melting metals columbium, molybdenum, tantalum, or tungsten. The association of high-melting metals with the specimens showing an absence of diffusion layers is not unexpected, for it is known that rates of diffusion at a given temperature are lower the higher the melting points of the metals involved.¹

It should be remembered that in the case of Mo-W and other alloy systems which contain no intermediate phases one would ordinarily not expect to observe reaction layers or any change in the microstructure at the interface. Terminal solid solutions formed by interdiffusion of two metals are continuous with the pure metals and thus cannot ordinarily be visibly defined by metallographic techniques. A change in microstructure might appear, however, if microconstituents resulting from impurities showed differing solubilities in the solid solutions compared to the originally pure metal. In some specimens there were indications that such a process had taken place.

Table II lists those diffusion couples which gave uncertain results. Most of the combinations listed are those which appeared to have reacted, but either the reaction layers were so thin that accurate measurement was not possible or a zone with poorly defined limits was observed. The remainder of the combinations are those which yielded non-reproducible data, probably owing to separation of the interface during the diffusion anneals.

Table I

DIFFUSION COUPLES IN WHICH NO REACTION LAYERS WERE
NOTED AFTER 6 DAYS OR MORE

<u>500°</u>	<u>600°</u>	<u>650°</u>	<u>700°</u>	<u>800°</u>
Cb-Fe	Cb-U	Fe-Zr	Be-W	Mo-W
Cb-Mo	Fe-Mo	Mo-Ta	Cb-Ta	
Cb-Ni	Fe-Ta		Cb-W	
Cb-Ta	Fe-W		Fe-W	
Cb-W	Mo-Ni		Fe-Zr	
Cb-U	Mo-Ta		Mo-Ta	
Cb-Zr	Mo-W		Mo-W	
Fe-Mo	Ni-Ta		Ta-347 S.S.	
Fe-Ta	Ni-W		W-Zr	
Fe-W	Ta-347 S.S.		W-347 S.S.	
Mo-Ta	W-347 S.S.			
Mo-W				
Mo-347 S.S.				
Ni-W				
Ta-347 S.S.				
Ti-347 S.S.				

Table II

DIFFUSION COUPLES IN WHICH UNCERTAIN RESULTS WERE
NOTED AFTER 6 DAYS OR MORE

<u>500°</u>	<u>600°</u>	<u>650°</u>	<u>700°</u>	<u>750°</u>
Fe-U	Ta-U	Fe-Mo	Cb-U	Cb-U
Fe-347 S.S.	W-U	Ta-347 S.S.	Cb-Mo	Fe-Ta
Mo-U			Cb-Fe	Fe-W
Ni-347 S.S.			Cb-347 S.S.	Mo-Ta
Ta-U			Fe-Ta	Ni-W
Ta-Zr			Mo-347 S.S.	Ta-U
W-U			Ni-W	Ta-347 S.S.
U-Zr			Ta-U	W-U
			W-U	W-347 S.S.

Figures 3, 4, 5, and 6(a) and (b) show log time vs. log thickness curves for reaction layers formed respectively at 500, 600, 650, and 700°C. The log-log plot of the data was chosen on the basis of results obtained in similar tests by Lustman and Mehl.² They found that the growth of diffusion reaction layers as a function of time may be represented by the general parabolic equation

$$X^n = Kt$$

where

X = thickness

n = reaction index

K = reaction-rate constant

t = time

For a given temperature, a particular value of n is found by taking the reciprocal of the slope of the straight line obtained when the logarithm of thickness is plotted against the logarithm of time.

The above equation provides a useful relation for extrapolation to times or layer thicknesses other than those plotted in Figures 3 and 6. To facilitate this, Table III was prepared, which lists values of n and K for the time-thickness curves presented. It is emphasized that those values of n and K which are based on only two data points should be considered as only tentative. In any case it should be remembered that use of metals which analyse appreciably different than the commercially pure materials used in this investigation may lead to different results because of the effect of differing amounts of additional elements on diffusion rates.

Data on the effect of temperature on the growth of reaction layers, though largely incomplete, are shown in Figure 7(a), (b), and (c) where the total layer thickness, T , formed in six days is plotted against the reciprocal of the absolute temperature of diffusion. In accordance with the findings of Lustman and Mehl² the data points, when more than two are available, appear to lie near straight lines. Exceptions are Be-Ni between 650° and 700°C. and Ni-347 stainless steel between 600° and 700°C.

By determining the slopes of the curves shown in Figure 7(a), (b), and (c) and using the Arrhenius equation $T = Ae^{-Q/RT}$, it is possible to obtain values of the activation energy for diffusion layer formation. Values of the activation energy Q , with the temperature ranges in which they were determined, are summarized in Table IV. The values of Q obtained from only two points are to be regarded as only tentative.

Table III

VALUES OF REACTION RATE CONSTANTS

Diffusion Couple	Temp., °C.	n	K, in./day
Be-Ni	500	7.6	4.6×10^{-23}
Be-Zr	500	1.7	1.7×10^{-6}
Ni-U	500	3.0	7.4×10^{-12}
U-347 S.S.	500	2.9	1.1×10^{-11}
Be-Ni	600	1.6	5.3×10^{-6}
Be-U	600	2.0	1.9×10^{-8}
Fe-U	600	2.6	7.9×10^{-13}
Mo-U	600	2.7	1.3×10^{-11}
Ni-U	600	3.0	3.9×10^{-11}
Ni-347 S.S.	600	1.3	2.1×10^{-6}
U-347 S.S.	600	2.5	1.4×10^{-8}
Be-Fe	650	1.2	6.0×10^{-5}
Be-Ni	650	1.2	7.3×10^{-5}
Be-Ta	650	2.2	7.6×10^{-9}
Be-Zr	650	1.5	2.6×10^{-5}
Be-347 S.S.	650	2.5	4.8×10^{-8}
Cb-Ni	650	0.7	2.4×10^{-4}
Cb-Zr	650	1.4	1.5×10^{-6}
Fe-Ni	650	2.3	2.9×10^{-8}
Mo-Zr	650	1.5	2.3×10^{-7}
Ni-Zr	650	1.9	2.2×10^{-9}
Ni-347 S.S.	650	1.6	7.0×10^{-7}
Ta-Zr	650	2.1	1.7×10^{-9}
Zr-347 S.S.	650	1.1	3.0×10^{-6}
Be-Cb	700	1.7	3.3×10^{-7}
Be-Fe	700	1.5	1.3×10^{-5}
Be-Mo	700	0.6	1.8×10^{-4}
Be-Ni	700	1.2	4.3×10^{-4}
Be-Zr	700	1.2	2.2×10^{-4}
Be-347 S.S.	700	2.3	1.6×10^{-7}
Cb-Ni	700	1.0	8.4×10^{-5}
Cb-Zr	700	2.3	2.6×10^{-8}
Fe-Mo	700	2.0	3.6×10^{-9}
Fe-Ni	700	2.2	5.5×10^{-8}
Mo-Ni	700	1.4	3.6×10^{-7}
Mo-U	700	1.3	4.1×10^{-5}
Mo-Zr	700	1.0	1.3×10^{-4}
Ni-Ta	700	0.6	1.1×10^{-3}
Ni-U	700	3.0	1.0×10^{-8}
Ni-Zr	700	0.7	9.6×10^{-4}
Ni-347 S.S.	700	1.5	1.1×10^{-6}
Ta-W	700	1.4	3.6×10^{-7}
Ta-Zr	700	2.0	6.0×10^{-9}
U-Zr	700	3.0	2.4×10^{-13}
Zr-347 S.S.	700	1.7	1.8×10^{-7}

Table IV

ACTIVATION ENERGIES FOR REACTION-LAYER FORMATION

<u>Diffusion Couple</u>	<u>Q, cal. per mole</u>	<u>Temp. Range, °C.</u>
Be-Fe	12,100	650-700
Be-Ni	2,800	500-650
Be-U	22,800	600-650
Be-Zr	11,300	500-700
Cb-Ni	98,600	650-700
Cb-Zr	62,800	650-700
Fe-Mo	20,800	650-800
Fe-Ni	3,300	650-700
Fe-U	20,400	600-700
Mo-Ni	29,400	700-800
Mo-U	41,200	600-800
Mo-Zr	59,500	650-700
Ni-Ta	35,700	700-800
Ni-U	16,800	500-700
Ni-Zr	93,000	650-700
Ta-Zr	13,200	650-700
U-347 S.S.	17,700	500-700
Zr-347 S.S.	70,000	650-700

Strength of Diffusion Bonds

Although all possible combinations of the metals (except titanium) were tested for strengths of bonds formed for six or more days at temperatures between 600 and 700°C., only a few yielded bonds strong enough for quantitative results. Most of the reaction layers were so weak that they could be easily broken and separated with the fingers. In those cases where strong bonds or welds did result, the two metals forming the bond were usually metals known to form terminal solid solutions with one another. This was especially noticeable in the case of uranium, which consistently formed strong bonds with columbium, molybdenum, and zirconium - metals which are believed to be among those most soluble in solid uranium. No particular correlation between shear strength and time or temperature of bond formation was noted, although the Mo-U bonds formed at 600° appeared to be somewhat stronger than those formed at 700°. The bond strength data are summarized in Table V. Those combinations of metals which do not appear in the table showed negligible shear strengths. Difficulty was experienced in obtaining unoxidized specimens for this series of tests. Under ideal conditions, with no oxide penetration into the diffusion interface, it is likely that diffusion bonds would be obtained with shear strengths substantially higher than those reported in Table V.

Table V

SHEAR STRENGTHS OF BONDS FORMED BY DIFFUSION AFTER
6 OR MORE DAYS AT 600° TO 700°C.

<u>Diffusion Couple</u>	<u>No. of Specimens Tested</u>	<u>Avg. Shear Strength of Bond, p.s.i.</u>	<u>Remarks</u>
Cb-U	6	4,000	
Fe-Ni	1	5,500	
Fe-U	2	5,500	Also two specimens showed negligible strength
Fe-347 S.S.	1	15,500	
Ni-347 S.S.	1	16,500	
Mo-U	10	10,000	
Zr-U	2	6,500	
Zr-U	1	5,500	Diffused one day only
Zr-347 S.S.	1	1,100	

Microstructural Characteristics of Reaction Layers

Figures 8 through 36 show photomicrographs of the reaction interfaces of metal combinations which were observed to form layers. The photomicrographs were made from specimens diffused at 700°C., with the exception of Be-Ta, which was diffused at 650°, and Ti-U and Ti-347, which were diffused at 500°.

Be-Cb (Figure 8). Two layers of widely varying thickness are noted at 650°, while only one layer was observed to form at 700°. A peritectic may occur between 650° and 700°. Layers appear to form mainly on columbium side of the interface.

Be-Fe (Figure 9). Two layers of widely varying thickness noted at 650° and 700°. Layers form mostly on the beryllium side of the interface.

Be-Mo (Figure 10). One layer, extremely thin, noted at 700°.

Be-Ni (Figure 11). Two layers noted at 500°, 600°, 650°, and 700°. The layer nearer the beryllium is much thicker and at 600° frequently showed a precipitated phase. In 700° tests the thick layer was observed to contain columnar grains, oriented perpendicularly to the interface.

Be-Ta (Figure 12). One layer observed at 650°. There are indications that the layer forms on the tantalum side of the interface.

Be-U (Figure 13). One layer observed at 600°, 650°, and 700°, which forms on the uranium side of the interface. The layer does not increase in thickness beyond about 0.0006", probably because of severe cracking which is noted in the beryllium near the interface. The amount of cracking increases as the test time is increased.

Be-Zr (Figure 14). A layer forms on the zirconium side of the interface, with acicular grains projecting into the zirconium from the interface. There is some indication that the layer may be composed of two compounds, for under polarized light a light-colored constituent is consistently observed near the interface.

Be-347 Stainless Steel (Figure 15). At 500° a very thin layer is noted. At 650° and 700° a thick layer is observed with an adjoining thinner layer containing a large proportion of precipitated particles.

Cb-Mo (Figure 16). Very thin irregular layer observed after 24 days at 700°.

Cb-Ni (Figure 17). At 650° two thin irregular layers appear on the columbium side of the interface. At 700° much thicker layers are noted.

Cb-U (Figure 18). At 700° a thin grey-colored irregular layer has been noted occasionally.

Cb-Zr (Figure 19). Two layers observed at 650° and 700°. The layer formed nearer the zirconium at 700° contains an acicular constituent with some tendency towards an orientation parallel to the interface.

Fe-Mo (Figure 20). A thin uniform layer forms at 650° and 700°. Two layers are observed at 800°.

Fe-Ni (Figure 21). Two layers observed at 650° and 700°. The layer nearer iron contains a fine-grained structure and may be partially transformed austenite.

Fe-U (Figure 22). An irregular grey-colored layer forms at 600° and 700°, apparently on the uranium side of the interface.

Fe-347 Stainless Steel (Figure 23). At 650° and 700° an irregular outlining of the iron grains near the interface is observed. No layer formation is noted.

Mo-Ni (Figure 24). At 650° one thin uniform layer is formed, while at 700° two layers are observed.

Mo-U (Figure 25). At 600° two thin irregular layers are observed. At 700° the layers are much thicker and are very uniform in thickness. The layer nearer the molybdenum frequently shows a gradation in response to etching, suggesting that it may cover a relatively large range of composition.

Mo-Zr (Figure 26). Two very thin layers observed at 650°. At 700° the layer nearer the zirconium is much thicker.

Ni-Ta (Figure 27). Two irregular layers observed at 700° and 800°.

Ni-U (Figures 28(a) and 28(b)). Two layers observed at 500°, three layers at 600°, and five or more at 700°. The layers all appear to lie on the uranium side of the interface. The layer which adjoins the uranium shows a very irregular boundary which, when examined with polarized light (Figure 28(b)), does not appear to be related to the grain structure of the uranium. The nickel side of the interface frequently shows much cracking; and if the diffusion bond is broken, fracture occurs through this area, leaving the reaction layers attached to the uranium.

Ni-Zr (Figure 29). Two layers are noted at 650°, and three or more are observed at 700°. The layers appear to form on the zirconium side of the interface.

Ni-347 Stainless Steel (Figure 30). One uniform layer forms at 600°, 650°, and 700°. The layer shows a fine-grained structure when heavily etched.

Ta-W (Figure 31). Two very irregular layers form at 700°.

Ta-Zr (Figure 32). One layer observed at 650°, and two noted at 700°. The layer adjoining the zirconium is similar in etching characteristics to a second phase originally present in the zirconium.

Ti-U (Figure 33). At least one irregular layer forms at 500°.

U-Zr (Figure 34). Thin layer noted, apparently formed on the uranium side of the interface.

U-347 Stainless Steel (Figure 35). One layer forms at 500°; three layers form at 600° and 700°. The center layer is severely cracked, and fracture occurs through this zone when the interface is separated. At 700°, the cracking appears to prevent diffusion after about 0.004" of layers have been formed.

Zr-347 Stainless Steel (Figure 36). One layer observed at 650° and 700°. The layer forms on the zirconium side of the interface.

Miscellaneous Tests

Distortion due to cold work and recrystallization following cold work have been known in some cases to affect diffusion rates.¹ To determine possible effects of cold work on the rate at which reaction layers are formed between molybdenum and uranium, tests were made in which uranium was reacted with molybdenum which had been cold rolled to reductions of 0, 10, 20, 40, and 80 per cent. The test temperature, 700°C., was about 200° below the recrystallization temperature of the molybdenum. Metallographic examination showed no differences in the total thickness of the layers which formed.

To determine possible effects of recrystallization on the rate of formation of reaction layers between nickel and uranium, a similar series of tests was made in which the nickel was given cold reductions up to 80 per cent and diffused with uranium. In this case the test temperature, 700°C., was about 100° above the recrystallization temperature of the nickel. Again, no differences in reaction rate were found.

In conclusion, acknowledgment is made to Lowell T. Lloyd, who performed the early tests, and to Maurice Odie, who did the metallography and photomicrography.

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Figure 1. Diffusion Specimens and Holder.

Figure 2. Specimen used for Testing Shear Strengths of Diffusion Bonds.

Figure 3. Thickness of Reaction Layers Formed at 500°C.

Figure 4. Thickness of Reaction Layers Formed at 600° C.

Figure 5. Thickness of Reaction Layers Formed at 650° C.

Figure 6(a). Thickness of Reaction Layers Formed at 700° C.

Figure 6(b). Thickness of Reaction Layers Formed at 700° C.

Figure 7(a). Thickness of Reaction Layers Formed in 6 Days.

Figure 7 (b). Thickness of Reaction Layers Formed in 6 Days.

Figure 7(c). Thickness of Reaction Layers Formed in 6 Days.

No. 5674

250x

Figure 8
Be-Cb. Twelve days at 700°C.

No. 5663

250x

Figure 9
Be-Fe. Twelve days at 700°C.

No. 5667

250x

Figure 10
Be-Mo. Twelve days at 700°C.

No. 5669

100x

Figure 11
Be-Ni. Twelve days at 700°C.

No. 5872

250x

Figure 12
Be-Ta. Twelve days at 650°C.

No. 5530

250x

Figure 13
Be-U. Twelve days at 700°C.

No. 5769 100x

Figure 14
Be-Zr. Twenty-four days at 700°C.

No. 5660 250x

Figure 15
Be-347 Stainless Steel. Twelve days at 700°C.

No. 5786 500x

Figure 16
Cb-Mo. Twenty-four days at 700°C.

No. 5679 250x

Figure 17
Cb-Zr. Twelve days at 700°C.

No. 5164 500x

Figure 18
Cb-U. Twelve days at 700°C.

No. 5693 250x

Figure 19
Cb-Zr. Twelve days at 700°C.

No. 5678 250x

Figure 20
Fe-Mo. Twelve days at 700°C.

No. 5676 250x

Figure 21
Fe-Ni. Twelve days at 700°C.

No. 5142 500x

Figure 22
Fe-U. Twelve days at 700°C.

No. 5614 250x

Figure 23
Fe-347 Stainless Steel. Six days at 700°C.

No. 5680 500x

Figure 24
Mo-Ni. Twelve days at 700°C.

No. 5227 250x

Figure 25
Mo-U. Eighteen days at 700°C.

No. 5655 250x

Figure 26
Mo-Zr. Twelve days at 700°C.

No. 5677 500x

Figure 27
Ni-Ta. Twelve days at 700°C.

No. 5342 250x

Figure 28-a
Ni-U. Six days at 700°C.

No. 6561 150x

Figure 28-b
Ni-U. Twelve days at 700°C.
Polarized light.

No. 5531 250x

Figure 29
Ni-Zr. Twelve days at 700°C.

No. 5659 250x

Figure 30
Ni-347 Stainless Steel. Twelve
days at 700°C.

No. 5775

500x

Figure 31
Ta-W. Twenty-four days at 700°C.

No. 5533

500x

Figure 32
Ta-Zr. Twelve days at 700°C.

No. 6537

500x

Figure 33
Ti-U. Twenty-four days at
500°C.

No. 5510

1000x

Figure 34
U-Zr. Six days at 700°C.

No. 5504

250x

Figure 35
U-347 Stainless Steel. Six days at
700°C.

No. 5658

250x

Figure 36
Zr-347 Stainless Steel. Twelve
days at 700°C.

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