WAPD-TM-167

AEC RESEARCH AND
DEVELOPMENT REPORT

HIGH-TEMPERATURE WATER AND STEAM-CORROSION BEHAVIOR OF ZIRCONIUM-URANIUM ALLOYS

JULY 1959

CONTRACT AT-11-1-GEN-14

BETTIS PLANT—PITTSBURGH, PA. OPERATED FOR THE
U.S. ATOMIC ENERGY COMMISSION BY BETTIS ATOMIC
POWER DIVISION, WESTINGHOUSE ELECTRIC CORPORATION

DISCLAIMER

WAPD-TM-167

UC-25: Metallurgy and Ceramics
TID-4500 (14th Ed.)

HIGH-TEMPERATURE WATER AND STEAM-CORROSION BEHAVIOR OF ZIRCONIUM-URANIUM ALLOYS

Stanley Kass

Contract AT-11-1-GEN-14

July 1959

Price $ .75
Available from the Office of Technical Services,
Department of Commerce,
Washington 25, D. C.

BETTIS PLANT • PITTSBURGH, PA.
OPERATED FOR THE U. S. ATOMIC ENERGY COMMISSION BY
BETTIS ATOMIC POWER DIVISION, WESTINGHOUSE ELECTRIC CORPORATION

STANDARD EXTERNAL DISTRIBUTION

	No. Copies
UC-25: Metallurgy and Ceramics, TID-4500, 14th Edition	566

SPECIAL EXTERNAL DISTRIBUTION

Manager, Pittsburgh Naval Reactors Operations Office, AEC	3
TOTAL	569

CONTENTS

Weight-change vs time curves expressing the corrosion behavior of zirconium alloys containing additions of 10 through 60 w/o uranium tested in 600 and 680°F water and in 750°F steam at 1500 psi are presented. The effects of various heat treatments on the subsequent corrosion properties are also included.

HIGH-TEMPERATURE WATER AND STEAM-CORROSION BEHAVIOR OF ZIRCONIUM-URANIUM ALLOYS

Stanley Kass

This report is a summary of all relevant available data describing the corrosion of zirconium alloys containing 10 to 60 w/o uranium in high-temperature water and steam, as well as the effects of heat treatment on the corrosion resistance.

TABLE I

ZIRCONIUM ALLOYS INCLUDED IN THE PROGRAM

Ingot No.	w/o Uranium
014	10.3 a*
054	15.8 a
028	19.8 a
J-777	20 b**
056	35.0 a
J-499	40 b
J-742	50 b
E-374	48.7 a
032	50.5 a
420	50.1 a
398	51.3 a
138	49.5 a
062	60.5 a

*actual
**nominal

Comprehensive studies to evaluate the corrosion behavior of zirconium-uranium alloys in pressurized, high-temperature water and steam were conducted at the Bettis Atomic Power Division and other installations because these alloys represent potential fuel materials for water-cooled and moderated nuclear reactors. Reports summarizing the results of the studies have been issued (Refs 1, 2, and 3); however, the detailed data describing the effects of heat-treatment and uranium content have not been included in these previous reports.

EXPERIMENTAL PROCEDURES

Ingot Fabrication

Fifteen-, twenty-, and fifty-lb ingots were prepared from sponge zirconium and derby uranium, using conventional double-arc melting procedures in an argon atmosphere. The ingots were then forged at 1850°F and rolled at 1450°F to 0.150-in. strip. Table I lists the nominal and actual compositions of the alloys studied.

Heat Treatment

Heat treatments, summarized in Table II, were performed in sealed, evacuated Vycor bulbs. The bulbs for the high-temperature treatments were evacuated to less than 0.03 micron, then, helium at 25 cm Hg pressure was added.

TABLE II

LIST OF HEAT TREATMENTS STUDIED

Heat Treatment No.	
1	4 hr at 800°C, air cooled, then 4 hr at 620°C, furnace cooled
2a	4 hr at 850°C, water quenched
2b	4 hr at 900°C, water quenched
2c	4 hr at 1000°C, water quenched
3	4 hr at 850°C, furnace cooled
4	4 hr at 650°C, water quenched
5a	24 hr at 575°C, furnace cooled
5b	4 hr at 575°C, water quenched
6a	4 hr at 850°C, water quenched, then 1 hr at 575°C, furnace cooled
6b	4 hr at 850°C, water quenched, then 10 hr at 575°C, furnace cooled
6c	4 hr at 850°C, water quenched, then 30 hr at 575°C, furnace cooled
6d	4 hr at 850°C, water quenched, then 100 hr at 575°C, furnace cooled
7a	4 hr at 850°C, water quenched, then 1 week at 360°C, furnace cooled
7b	4 hr at 850°C, water quenched, then 3 weeks at 360°C, furnace cooled
7c	4 hr at 850°C, water quenched, then 5 weeks at 360°C, furnace cooled
8	As-fabricated
9a	4 hr at 850°C, water quenched, then 1 week at 400°C, furnace cooled
9b	4 hr at 850°C, water quenched, then 3 weeks at 400°C, furnace cooled
9c	4 hr at 850°C, water quenched, then 5 weeks at 400°C, furnace cooled

Sample Preparation

Specimens 1-in. x 0.5-in. x 0.1-in. were machined to a 63 μin. rms finish from the 0.150-in. thick heat treated hot-rolled strip. Before testing, the specimens were lightly abraded to remove any surface contamination brought about by the heat treatment, washed in Alconox, rinsed thirty minutes in tap water, rinsed in ethyl alcohol, and dried.

Test Conditions

Four specimens representing each heat treatment were exposed under static conditions to 316°C (600°F) or 360°C (680°F) water at saturation pressure, or in 400°C (750°F) steam at 1500 psi in externally heated, 1800-ml capacity, AISI Type 347 stainless steel autoclaves. Temperature control was maintained at ±5°F. The test water was passed through a mixed bed demineralizer to give a specific resistivity of greater than 500,000 ohm-cm. The autoclaves were filled with sufficient water to give a 20% vapor space at temperature. The number of specimens tested in the autoclave was adjusted to insure complete immersion. The water in the 316 and 360°C tests was degassed by venting the autoclaves for short periods at a temperature between 100 and 150°C. The autoclaves

used for the 400°C steam tests were initially vented to maintain 1500 psi. The specimens were supported on stainless steel wire-mesh trays and did not rest upon one another, nor were they electrically insulated from each other or the autoclave. After each test period, the specimens were scrubbed with a soft brush to remove all loose oxide and were weighed to the nearest 0.2 mg.

EXPERIMENTAL RESULTS

The corrosion behavior is presented in terms of weight change per unit area* during corrosion testing as a function of time in test for each alloy at each test temperature. The several heat treatments for each given alloy are compared. It should be noted that the weight change for these alloys is generally a weight loss, and the experimental points can best be fitted by straight lines. Thus, equations of the form $w = kt$ can be written to represent the relationship between weight loss and time. Rate constants were calculated from the graphically determined slopes and were plotted as a function of uranium content for a given temperature. The effect of temperature on the rate constants was determined by plotting the logarithm of the rate constant as a function of the reciprocal of the absolute temperature.

Zirconium + 10 w/o Uranium Alloys

The 360°C (680°F) water corrosion behavior of the zirconium + 10 w/o uranium alloys is shown in Figs. 1, 2, 3, and 4,** where the weight change is plotted as a function of time for each of the various heat treatments studied.

The effect of quenching temperature on the resultant 360°C water corrosion of the 10 w/o uranium alloys is evident in Fig. 1. Specimens quenched from 850, 900, and 1000°C exhibited the optimum corrosion resistance. The oxide films produced were thin and adherent throughout the test. In contrast, the specimens quenched from 575 and 650°C initially produced adherent oxide films; however, film breakdown occurred within 7 days of exposure, followed by general spalling. It should be noted in Fig. 1 that the specimens quenched from 575°C exhibited lower corrosion-loss rates and weight changes than those quenched from 650°C.

The effects of annealing temperature are shown in Fig. 2. The as-fabricated specimens, and specimens annealed at 575°C and slow cooled, exhibited similar corrosion behavior; the films were initially adherent, then slowly spalled. Specimens furnace-cooled from 850°C revealed lower corrosion resistance, while those air-cooled from 800°C, reannealed at 620°C, and furnace cooled, exhibited the least resistance. A comparison of the curves in Figs. 1 and 2 shows that the corrosion resistance of the specimens which were heated at 575°C is independent of cooling rate.

Figure 3, which depicts the 360°C water corrosion resistance of specimens quenched from 850°C and subsequently aged for 1, 10, 30, and 100 hr at 575°C and slow cooled, shows that a marked decrease in the corrosion resistance is brought about by aging at 575°C. The aged specimens exhibited spalling after 7 days of exposure, and the corrosion rate increased with increasing annealing time. It should be noted that the specimens quenched from the beta region and aged at 575°C for 30 and 100 hr (Fig. 3) corroded more rapidly than the samples annealed at 575°C for 4 hr and quenched (Fig. 1) or for 24 hr and furnace-cooled (Fig. 2).

Aging the 850°C quenched specimens at 360°C (680°F) (the corrosion test temperature) resulted in a very slight increase in the corrosion rate; however, no further decrease in corrosion resistance was observed when the aging time was increased from one to five weeks (Fig. 4). The oxide films produced were adherent throughout the test (approximately 180 days). The significant feature is that the samples were still gaining weight.

---

* Changes in area as a result of metal loss from corrosion were not factored into the calculations.

** All figures are found at the end of this report.

The effect of test temperature on the corrosion behavior of the 10 w/o uranium alloy samples, slow cooled from 575° C, is shown in Fig. 5. The corrosion rates vary from -0.017 mg/cm^2-hr at 316°C to -0.025 mg/cm^2-hr at 360°C and 0.046 mg/cm^2-hr at 400°C.

Zirconium + 15 w/o Uranium Alloys

In general, the behavior of the 15 w/o uranium alloys in water was very similar to the behavior of the 10 w/o alloys.

Quenching from the high temperature phase (850 to 1000°C) resulted in maximum corrosion resistance and adherent oxide films. Quenching from 575 and 650°C resulted in weight losses (non-adherent oxides) and decreased corrosion resistance (Fig. 6).

The corrosion resistance of material, slow cooled from the heat treating temperature (Fig. 7), decreased as the annealing temperature increased. Furthermore, the behavior of the specimens heat treated at 575°C was not influenced by cooling rate from the heat treating temperature (Figs. 6 and 7).

Aging the high temperature (850°C) quenched specimens at 575°C, and cooling slowly, produced deleterious effects upon the corrosion resistance (Fig. 8). While the as-quenched specimens showed adherent oxides throughout the test, specimens aged at 575°C and furnace cooled exhibited early spalling. The specimens held at 575°C for 10, 30, and 100 hr corroded more rapidly than those aged for 1 hour.

The effect of aging at the corrosion test temperature (360°C) on the corrosion behavior of 850°C quenched specimens is illustrated in Fig. 9. Slightly lower weight gains were obtained from the aged specimens throughout this test (210 days); however, it is difficult to state whether the lower weight gains reflected slight spalling, variations in weight change measurement, or improved resistance enhanced by the treatment.

Figure 10 shows the effect of temperature on the corrosion behavior of specimens slowly cooled from 575°C. The water tested specimens exhibited weight losses throughout the test; however, the specimens tested in 400°C steam exhibited weight gains after 7 days of exposure, then spalled. The corrosion rate increased from -0.022 to -0.048 to -0.982 mg/cm^2-hr as the temperature increased from 316 to 360 to 400°C, respectively.

Zirconium + 20 w/o Uranium Alloys

The effect of quenching temperature on the water corrosion behavior of the zirconium + 20 w/o uranium alloys is illustrated in Fig. 11. Quenching from the high temperature (850 to 1000°C) resulted in adherent oxide films and weight gains, while quenching from 575 and 650°C resulted in spalling oxides and weight losses. For the gamma quenched material, increasing the quenching temperature from 850 to 1000°C decreased the corrosion resistance.

Slow cooling after heat treating resulted in non-corrosion resistant forms of the alloys (Fig. 12). All specimens spalled within very short exposure times. Gamma (850°C) quenched specimens, subsequently aged for 1, 10, 30, and 100 hr at 575°C and slow cooled, resulted in impaired corrosion resistance (Fig. 13). All aged specimens exhibited spalling, oxide films, and weight losses. The specimens aged for 10, 30, and 100 hr revealed higher weight losses than those specimens aged for 1 hour.

The corrosion behavior of samples, gamma quenched and subsequently annealed for 1, 3, and 5 weeks at 360°C (680°F), is shown in Fig. 14 and illustrates that adherent films were obtained. Specimens aged for 3 and 5 weeks show lower weight gain values than the specimens aged for 1 week.

Specimens furnace cooled from 575°C and subsequently tested in 400°C (750°F) steam exhibited weight gains at the onset of corrosion, then spalled rapidly, resulting in high weight losses (Fig. 15).

The corrosion rate also increased from -0.029 to -0.066 to -0.162 mg/cm^2-hr as the test temperature was increased from 316 to 360 to 400°C.

Zirconium + 35 w/o Uranium Alloys

Alloys containing 35 w/o or greater uranium exhibited markedly different behavior in water than was observed for the lower uranium alloys. The corrosion of the 35 w/o alloy was relatively insensitive to prior thermal history (although some differences were observed) and exhibited an early breakdown of the oxide film, resulting in general spalling. Specimens quenched from 575 and 850°C exhibited similar corrosion properties, while those quenched from 650 and 900°C exhibited slightly higher weight losses (Fig. 16). No difference in the corrosion behavior was noted for specimens slow cooled from the high or low temperatures (Fig. 17). It should be further noted that the slow-cooled material corroded in a manner similar to the 650 and 900°C quenched material. Aging the as-quenched specimens at 575°C resulted in slightly lower corrosion resistance (Fig. 18); while aging at 360°C brought about very slight changes in the weight losses (Fig. 19).

The effect of corrosion test temperature (illustrated in Fig. 20) shows the increase in corrosion rate from -0.050 to -0.150 to -0.264 mg/cm^2-hr as the test temperature was increased from 316 to 360 to 400°C.

Zirconium + 50 w/o Uranium Alloys

The corrosion behavior of the 50 w/o uranium alloy is summarized in Figs. 21, 22, 23, and 24, showing that the corrosion rate was relatively insensitive to thermal treatment and cooling rate. Furthermore, the corrosion resistance of the material quenched from 850°C was not altered by aging at 360, 400, or 575°C.

The corrosion rates of the alloys increased with increasing test temperature (Fig. 25). The rate increased from -0.083 to -0.25 to -0.80 mg/cm^2-hr as the temperature increased from 316 to 360 to 400°C.

Zirconium + 60 w/o Uranium Alloys

The corrosion resistance of the zirconium alloys containing approximately 60 w/o or more uranium differed from that of 35 and 50 w/o alloys. The corrosion was markedly affected by heat treatment. After appropriate heat treatments, the corrosion process was characterized by slow general corrosion followed by very rapid, accelerated corrosion and disintegration. Other heat treatments resulted in higher general corrosion and spalling without disintegration.

Figure 26 depicts the water corrosion behavior of specimens quenched from 575, 650, 850, 900, and 1000°C. Specimens quenched from 850°C or higher disintegrated within 9 days of exposure. The corrosion life (time for complete disintegration) increased as the quenching temperature was decreased from 800 to 650 to 575°C. Furthermore, the corrosion rate of the 650°C quenched specimens prior to disintegration was approximately 40% of that obtained when the specimens were quenched from 575°C.

Slow cooling after heating in the temperature range from 575 to 1000°C (Fig. 27) resulted in lower corrosion rates and longer lives than when the material was rapidly cooled.

Aging the 850°C quenched specimens at 575°C dramatically increased the corrosion life. The corrosion resistance, however, decreased with increasing aging time. Specimens aged 1, 10, 30, and 100 hr exhibited corrosion lives of 93, 93, 93, and 65 days respectively, in comparison to 3 days for unaged specimens. It was also observed that maximum corrosion resistance was obtained when 1-hr, 575°C aging was employed (see Fig. 28).

Aging at 360 and 400°C also markedly affected the corrosion behavior of the quenched samples (Figs. 29 and 30). Specimens aged for 1 week at 360°C had lives of 58 days, while those aged for

3 and 5 weeks had 100-day lives. A one- or three-week age at 400°C produced specimens which did not exhibit disintegration within 100 days of exposure; however, specimens aged for 5 weeks at 400°C disintegrated within 60 days of test.

The corrosion rate vs test temperature relationship for 60 w/o uranium alloys, slow cooled from 575°C, is shown in Fig. 31. It should be noted that the specimens tested in 400°F steam were completely corroded within 15 days of test.

SUMMARY

Figures 1-31 demonstrate that the corrosion behavior of the alloys can be characterized empirically by equations of the form $w = kt$ for each heat treatment and test temperature. The graphically determined rate constants for the alloys in 360°C water are shown in Table III and graphically presented in Fig. 32. Figure 32 shows that:

1) For gamma quenched material, the corrosion rate increases slowly as the uranium content of the alloy is increased from 10 to 50 w/o.
2) Similar behavior is noted for other heat treatments except for the 850°C furnace cooled material.
3) The specimens furnace cooled from 850°C show a linear relationship between corrosion rate and uranium content over the entire range of the alloys studied.

TABLE III

316°C (680°F) CORROSION RATES OF ZIRCONIUM-URANIUM ALLOYS

Heat Treatment	Corrosion Rate (mg/cm^2-hr)						
	10 w/o U	15 w/o U	20 w/o U	35 w/o U	40 w/o U	50 w/o U	60 w/o U
800°C AC*, 620°C FC**	-0.05	-0.07	-0.08	-0.15	-0.18	-0.27	-0.67
850°C, Quenched	+0.001	+0.007	+0.01	-0.11	-0.16	-0.24	F†
900°C, Quenched	+0.001	+0.006	+0.01	-0.15	-0.16	-0.24	F†
1000°C, Quenched	+0.001	+0.005	+0.01	--	-0.15	-0.24	F†
850°C, FC	-0.04	-0.06	-0.08	-0.15	-0.17	-0.26	-0.33
850°C, Quenched	-0.04	-0.07	-0.03	-0.14	-0.18	-0.25	-0.63
575°C, FC	-0.03	-0.05	-0.07	-0.15	-0.19	-0.28	-0.93
575°C, Quenched	-0.03	-0.05	-0.05	-0.16	-0.19	-0.27	-1.03
850°C, Quenched, + 1 hr at 575°C, FC	-0.02	-0.06	-0.06	-0.13	-0.16	-0.25	-0.32
+10 hr at 575°C, FC	-0.03	-0.06	-0.07	-0.16	-0.17	-0.25	-0.42
+30 hr at 575°C, FC	-0.04	-0.06	-0.07	-0.17	-0.17	-0.25	-0.45
+100 hr at 575°C, FC	-0.04	-0.06	-0.07	-0.16	-0.16	-0.25	-0.65
+1 week at 360°C, FC	+0.002	+0.006	+0.01	--	-0.15	-0.24	-0.38
+3 weeks at 360°C, FC	+0.002	+0.006	+0.01	--	-0.14	-0.24	-0.27
+5 weeks at 360°C, FC	+0.002	+0.006	+0.01	-0.16	-0.24	-0.29	--
+1 week at 400°C, FC	--	--	--	-0.16	--	-0.24	-0.31
+3 weeks at 400°C, FC	--	--	--	-0.13	--	-0.24	-0.32
+5 weeks at 400°C, FC	--	--	--	-0.14	--	-0.24	-0.33
As-fabricated	-0.02	-0.07	-0.07	-0.15	-0.17	-0.28	-0.43

*Air cooled
**Furnace cooled
†Failed by cracking within 9 days of test.

A graphic presentation of the effect of test temperature on the corrosion properties is included in Fig. 33. When the logarithm of the corrosion rate is plotted against the reciprocal of absolute temperature (Fig. 34), the straight line relationship predicted by the Arrhenius equation is obeyed by the 50 and 60 w/o alloys but not by the 10 to 35 w/o alloys.

DISCUSSION OF CORROSION BEHAVIOR

The corrosion behavior of the zirconium-uranium alloys has been thoroughly discussed and shown to be directly related to the phases present in the alloys (Refs 1, 3, 4, and 5). It will be discussed briefly here for purposes of review. The phase diagram as reported by Saller and Rough is shown in Fig. 35, and typical microstructures are shown in Figs. 36, 37, and 38.

Zirconium + 10 to 35 w/o Uranium Alloys

Quenching from the high temperature (850 to 1000°C) range results in a mixture of transformed beta zirconium and epsilon. As the uranium content increases, precipitation of the transformed beta phase is decreased and formation of the epsilon phase is accelerated. Thus, with increasing uranium content, increasing amounts of the epsilon phase are formed. Furthermore, as epsilon corrodes more rapidly than transformed beta zirconium, the corrosion resistance of the alloys should decrease with increasing uranium content.

The equilibrium structure, epsilon plus alpha zirconium, is obtained when the alloys are slowly cooled from all temperatures. However, the amount of the epsilon phase formed also increases with increasing uranium content; thus, the corrosion rates increase with increasing alloy uranium content. Differences between the quenched and slow-cooled specimens are attributed to the greater amounts of the epsilon phase which precipitate during slow cooling. Slight variations in the corrosion properties exhibited by individual alloys are to be expected because of the formation of alpha as well as differences in the distribution of the epsilon phase in the alpha zirconium matrix.

The alpha precipitate coalesces and coarsens when the alloys are held isothermally for extended periods of time in the temperature range around 600°C, which results in a continuous heavy network of epsilon. It has been postulated that the deleterious effects caused by aging at 575°C are caused by this heavy network of epsilon (Ref 1). Increasing corrosion rates should be obtained with increasing uranium content or increasing time at 575°C as the network becomes more continuous.

Isothermal-treatments at 360°C appear to have little or no effect upon the martensitic alpha (transformed beta) phase formed during direct quenching from the high temperature region; thus, the treatment produces no effect upon corrosion of individual alloys.

Zirconium + 50 w/o Uranium Alloys

Zirconium alloys containing approximately 45 to 55 w/o uranium are essentially single phase epsilon, since transformation starts very rapidly, even at temperatures as low as 260°C (Ref 5). Thus, the corrosion behavior is insensitive to heat treatment.

Zirconium + 60 w/o Uranium Alloys

Zirconium alloys containing more than 55 w/o uranium exhibit either the body-centered cubic gamma phase after quenching from high temperature, or epsilon plus alpha uranium phase after slow cooling from the high temperature or heating in the low temperature (less than 600°C) range.

The high corrosion rates, mechanisms, and associated disintegration (discontinuous failure) of the gamma phase alloys have been attributed to the oxidation of a metastable hydride of uranium which is precipitated during corrosion (Ref 7).

The corrosion of the aged and slow-cooled specimens is believed to be controlled by variations in the distribution of the alpha uranium network in the epsilon matrix resulting from time and temperature treatments.

REFERENCES

1. W. E. Berry and R. S. Peoples, "The Corrosion Behavior of Zirconium Uranium Alloys in High Temperature Water," Corrosion, Vol 14 (1958), p 414t.
2. S. Kass and K. M. Goldman, "Corrosion Behavior of Uranium-Zirconium Alloys in High Temperature Water and Steam," Bettis Atomic Power Division Technical Paper WAPD-T-416, (April 1958).
3. A. A. Bauer, S. Kass, and K. M. Goldman, "Physical Metallurgy and Properties of Zirconium-Uranium Alloys," Sec. U. N. Inter. Conf. on Peaceful Uses of Atomic Energy, A/CONF. 15/P/1785, (Jun 1958).
4. D. L. Douglass, L. L. Marsh, and G. K. Manning, "Transformation Kinetics of Zirconium-Uranium Alloys," Trans. ASM, Vol 50, (1958), p 305.
5. J. J. Kearns, "Transformation Kinetics of Uranium-Zirconium Alloys Containing 50 and 60 Wt Pct Uranium," Bettis Atomic Power Division Technical Paper WAPD-T-417, (Nov. 21, 1956).
6. H. A. Saller and F. A. Rough, "Compilation of U. S. and U. K. Uranium and Thorium Constitutional Diagrams," BMI-1000, (June 1, 1955).
7. M. W. Burkart and B. Lustman, "Corrosion Mechanism of Uranium-Base Alloys in High Temperature Water," Trans. AIME, Vol 212, (1958), p 26.

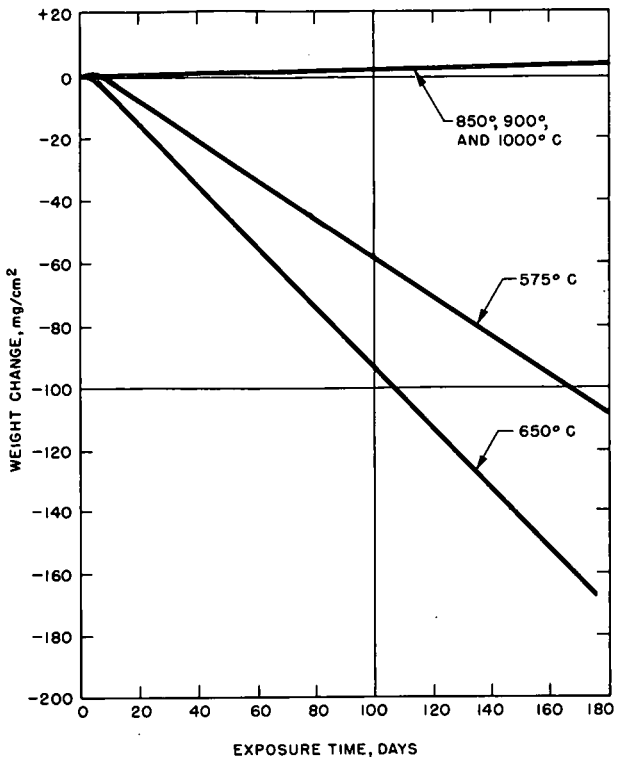


Fig. 1 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 10 w/o Uranium; Samples Quenched from Temperature

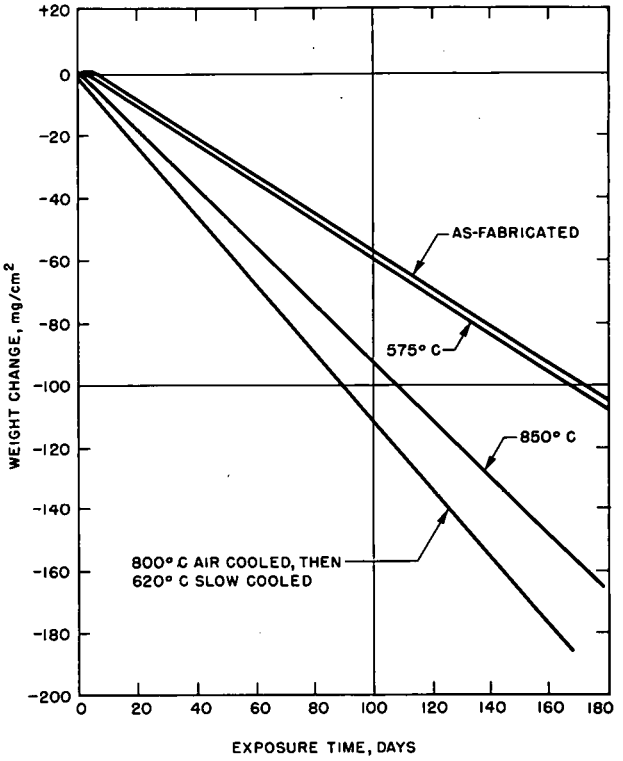


Fig. 2 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 10 w/o Uranium; Samples Slowly Cooled from Temperature

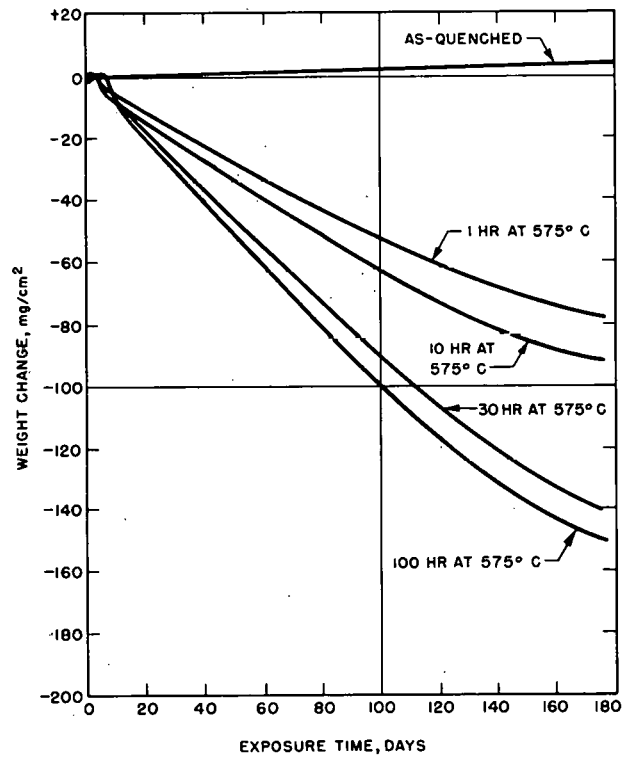


Fig. 3 360°C Water Corrosion of Zirconium + 10 w/o Uranium Quenched from 850°C, Subsequently Aged at 575°C, and Slowly Cooled

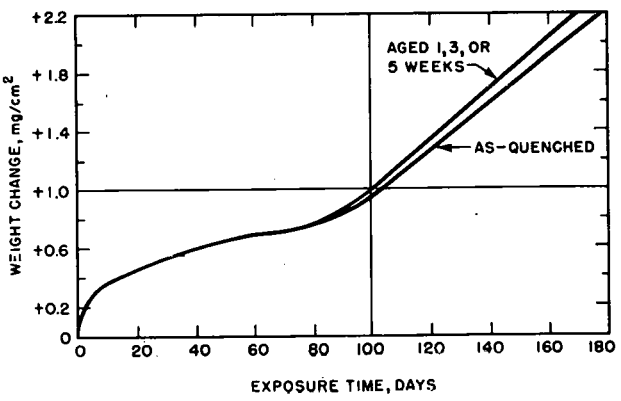


Fig. 4 360°C Water Corrosion of Zirconium + 10 w/o Uranium Quenched from 850°C, Subsequently Aged at 360°C, and Slowly Cooled

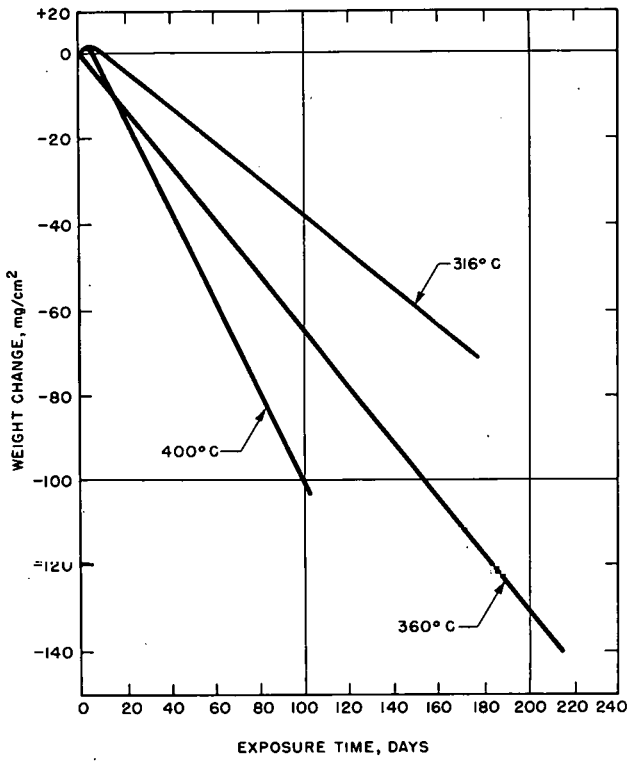


Fig. 5 *Effect of Temperature on the Corrosion of Zirconium + 10 w/o Uranium; Samples Slowly Cooled from 575°C*

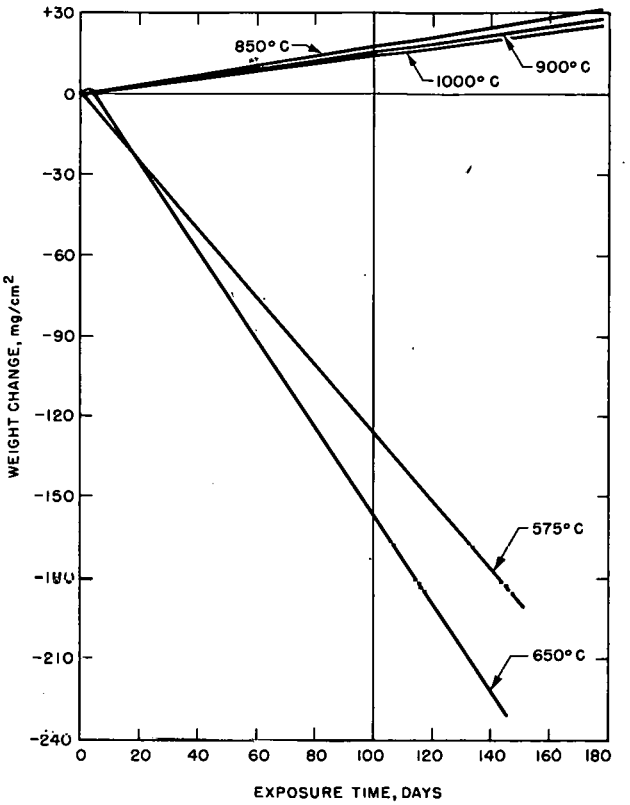


Fig. 6 *Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 15 w/o Uranium; Samples Quenched from Temperature*

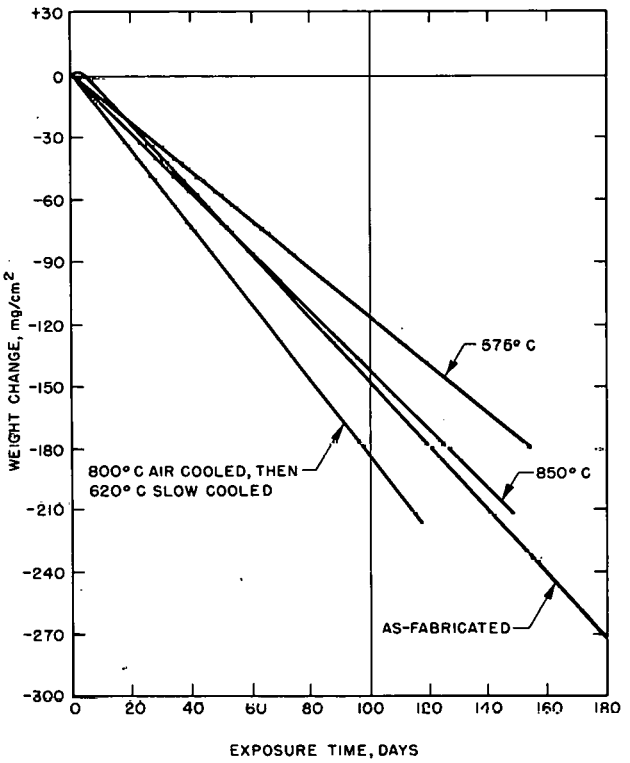


Fig. 7 *Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 15 w/o Uranium; Samples Slowly Cooled from Temperature*

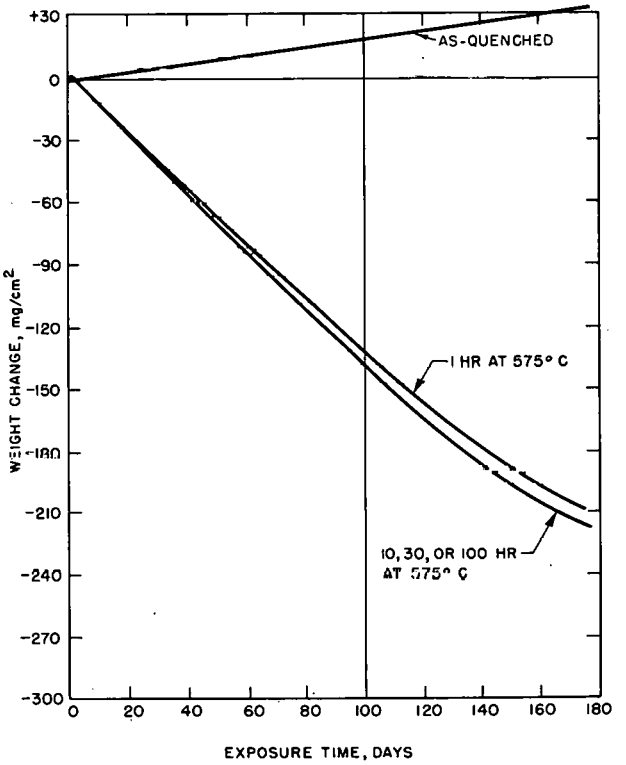


Fig. 8 *360°C Water Corrosion of Zirconium + 15 w/o Uranium; Quenched from 850°C, Subsequently Aged at 575°C, and Slowly Cooled*

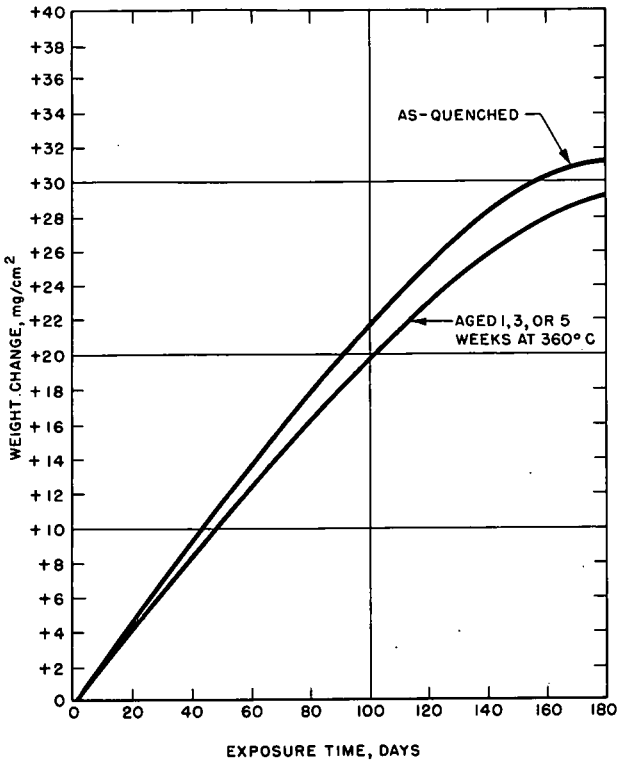


Fig. 9 360°C Water Corrosion Behavior of Zirconium + 15 w/o Uranium; Quenched from 850°C, Subsequently Aged at 360°C, and Slowly Cooled

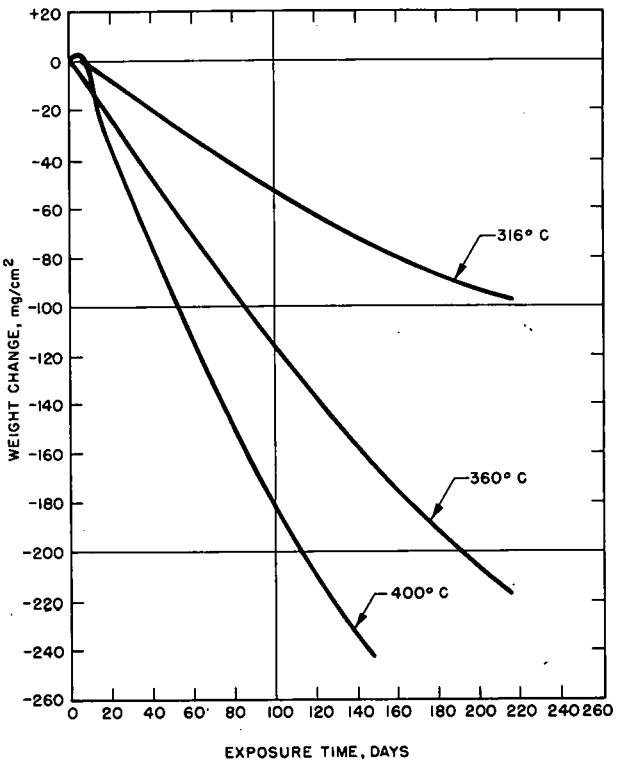


Fig. 10 Effect of Temperature on the Corrosion of Zirconium + 15 w/o Uranium; Samples Slowly Cooled from 575°C

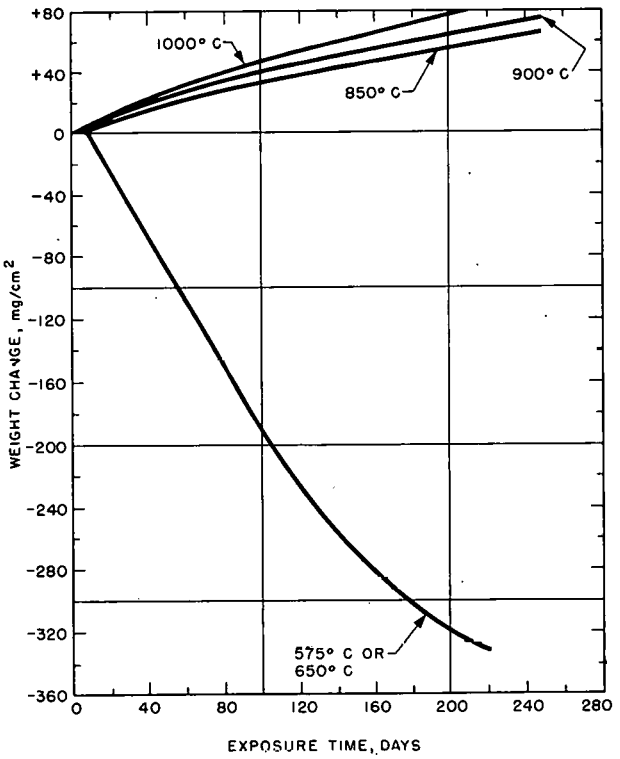


Fig. 11 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 20 w/o Uranium; Samples Quenched from Temperature

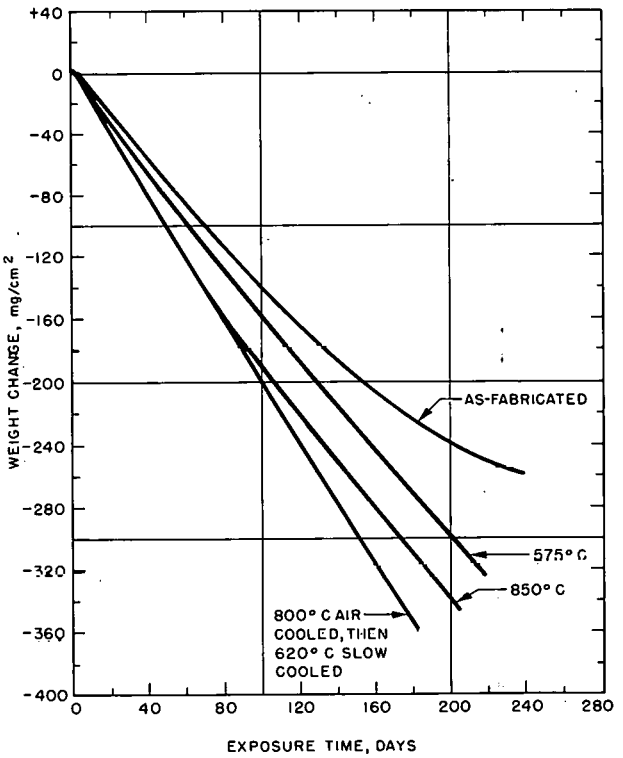


Fig. 12 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 20 w/o Uranium; Samples Slowly Cooled from Temperature

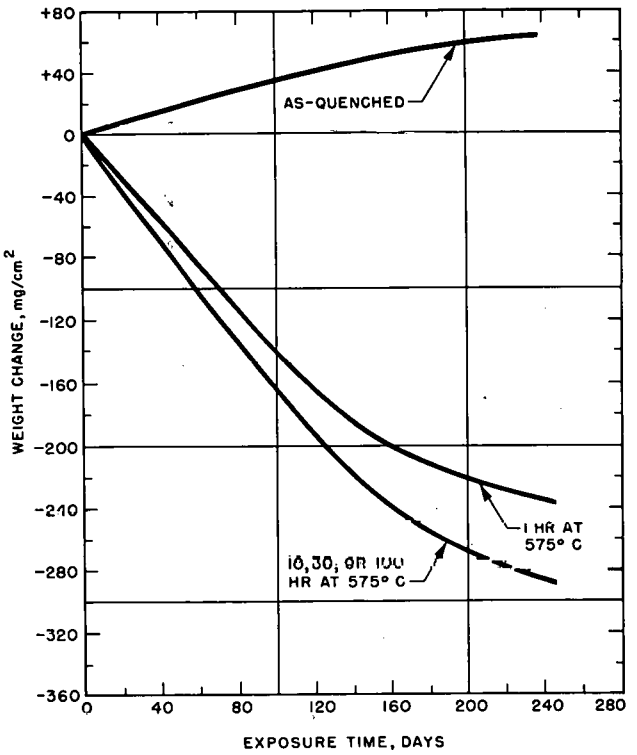


Fig. 13 360°C Water Corrosion of Zirconium + 20 w/o Uranium; Quenched from 850°C, Subsequently Aged at 575°C, and Slowly Cooled

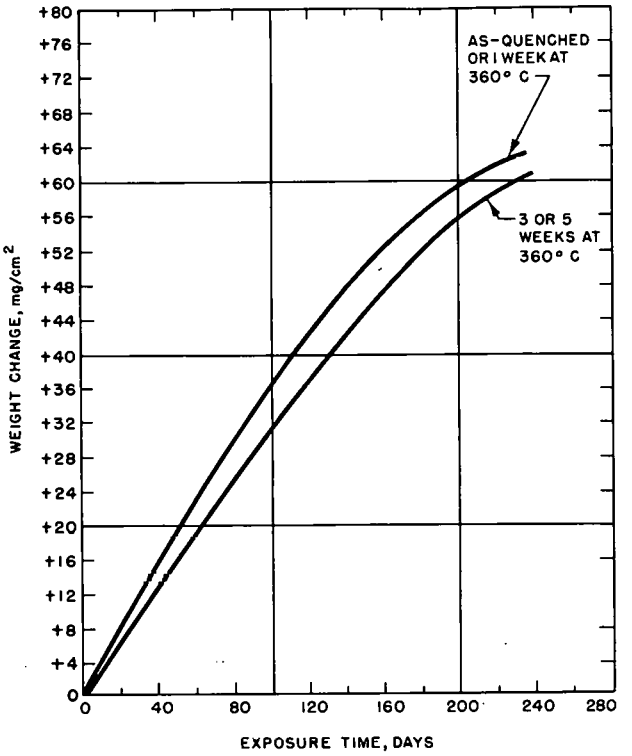


Fig. 14 360°C Water Corrosion of Zirconium + 20 w/o Uranium; Quenched from 850°C, Subsequently Aged at 360°C, and Slowly Cooled

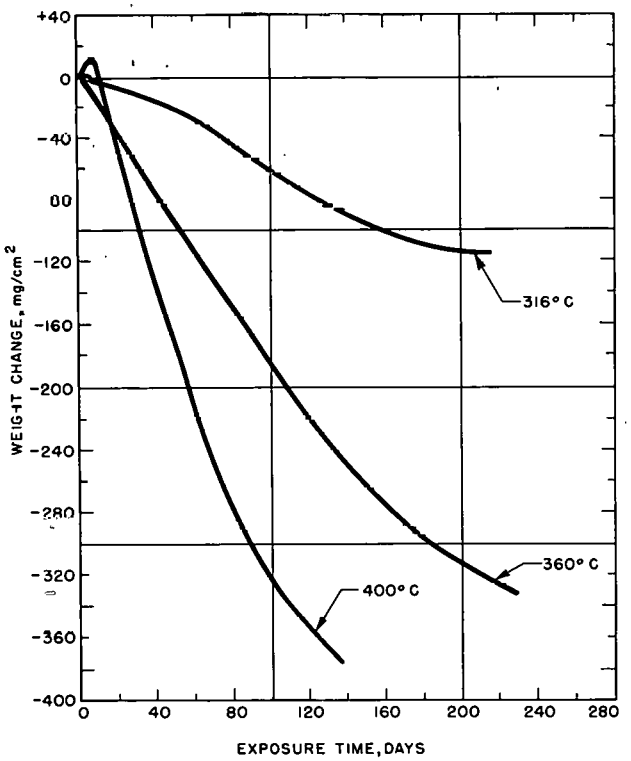


Fig. 15 Effect of Temperature on the Corrosion of Zirconium + 20 w/o Uranium; Samples Slowly Cooled from 575°C

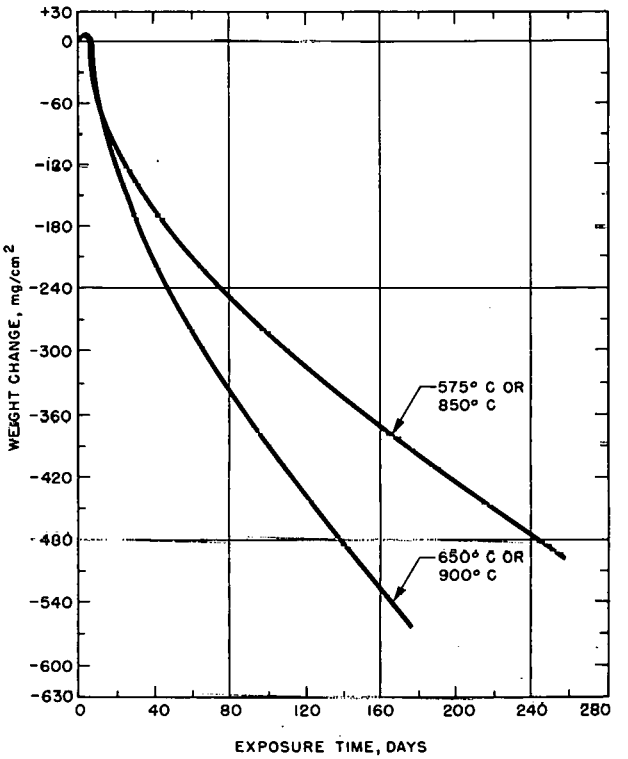


Fig. 16 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 35 w/o Uranium; Samples Quenched from Temperature

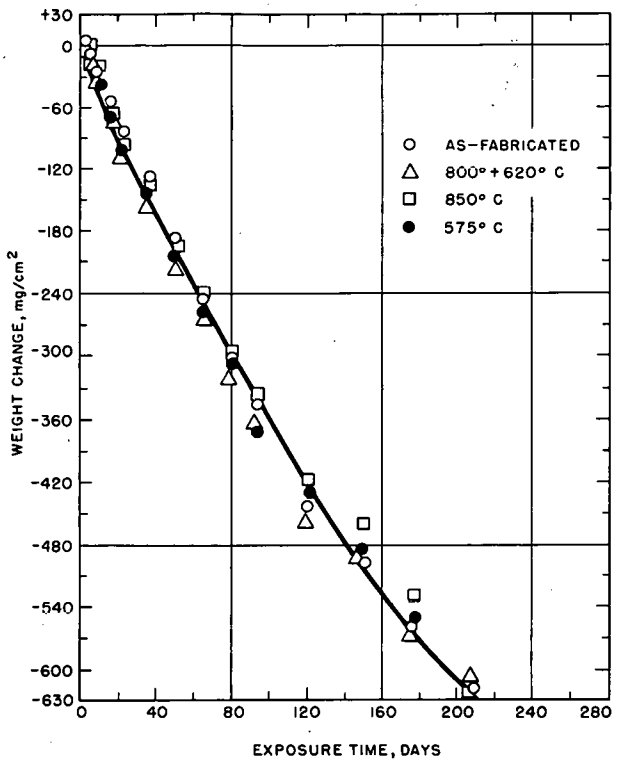


Fig. 17 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 35 w/o Uranium; Samples Slowly Cooled from Temperature

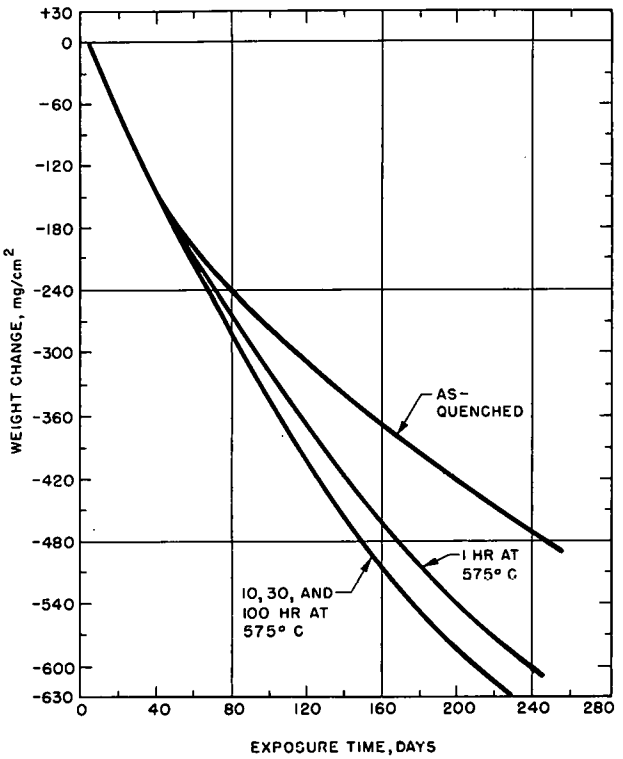


Fig. 18 360°C Water Corrosion of Zirconium + 35 w/o Uranium; Quenched from 850°C, Subsequently Aged at 575°C, and Slowly Cooled

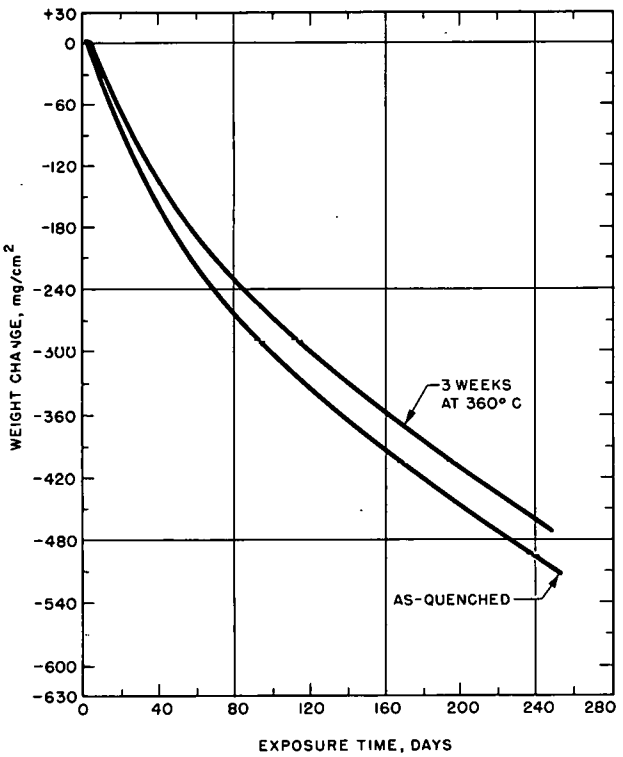


Fig. 19 360°C Water Corrosion of Zirconium + 35 w/o Uranium; Quenched from 850°C, Subsequently Annealed at 360°C, and Slowly Cooled

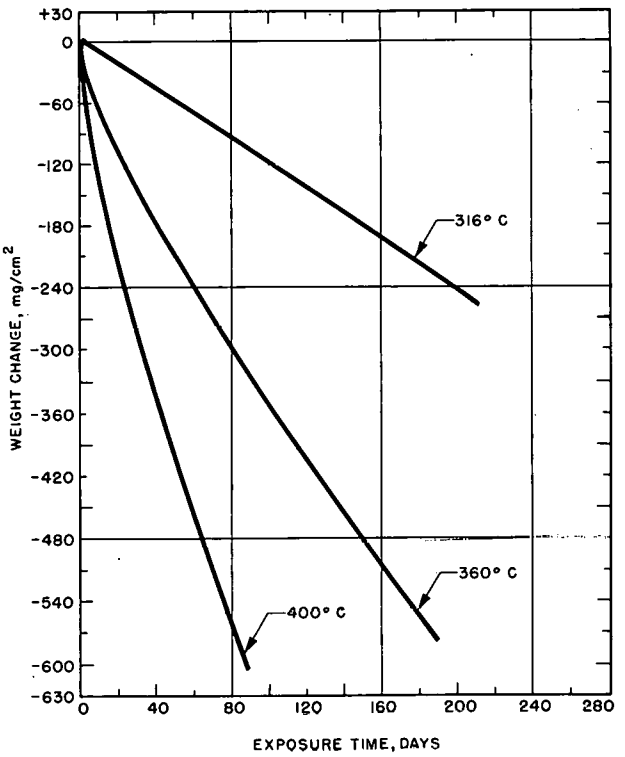


Fig. 20 Effect of Temperature on the Corrosion of Zirconium + 35 w/o Uranium; Samples Slowly Cooled from 575°C

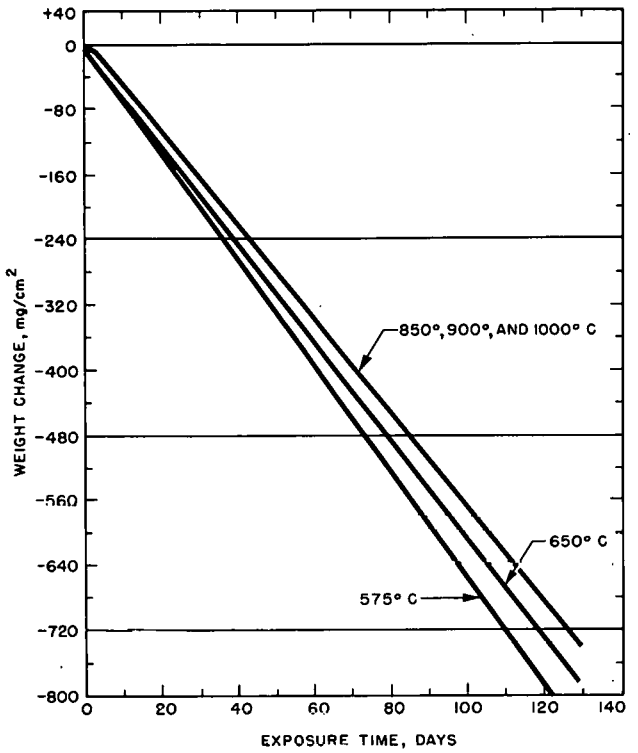


Fig. 21 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 50 w/o Uranium; Samples Quenched from Temperature

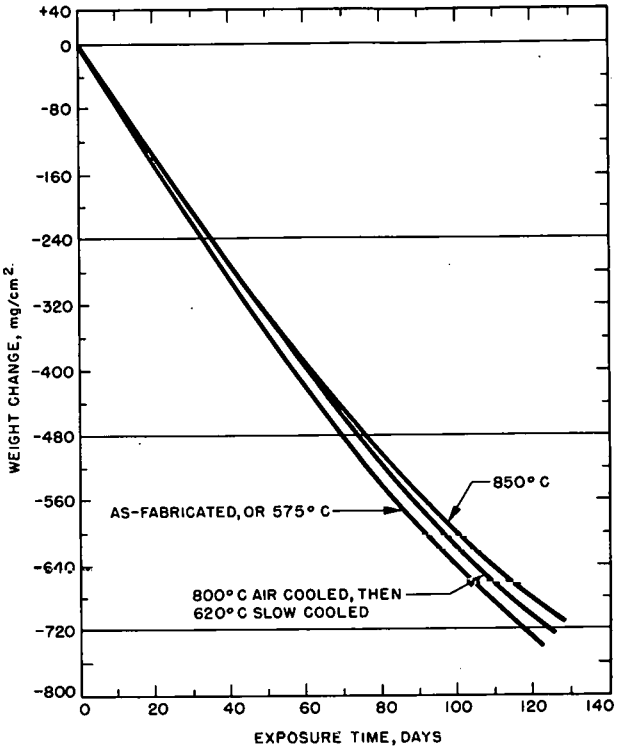


Fig. 22 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 50 w/o Uranium; Samples Slowly Cooled from Temperature

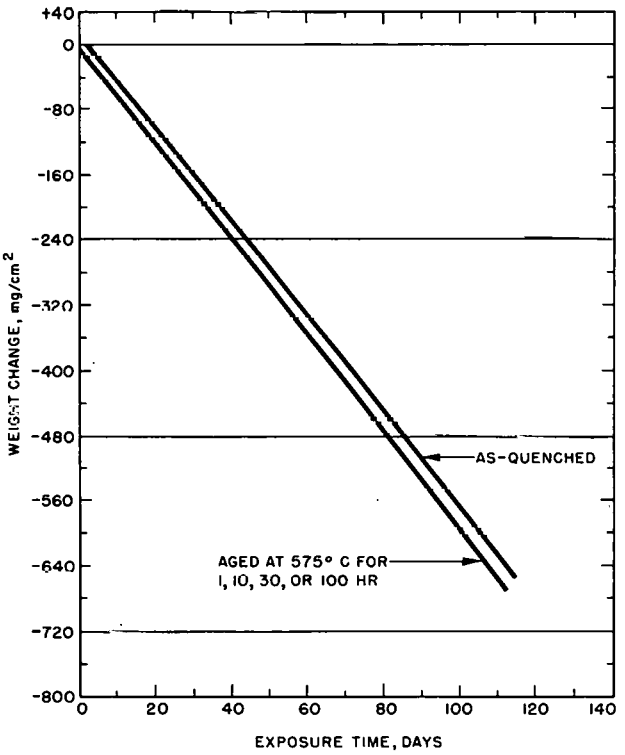


Fig. 23 360°C Water Corrosion of Zirconium + 50 w/o Uranium; Quenched from 850°C, Subsequently Annealed at 575°C, and Slowly Cooled

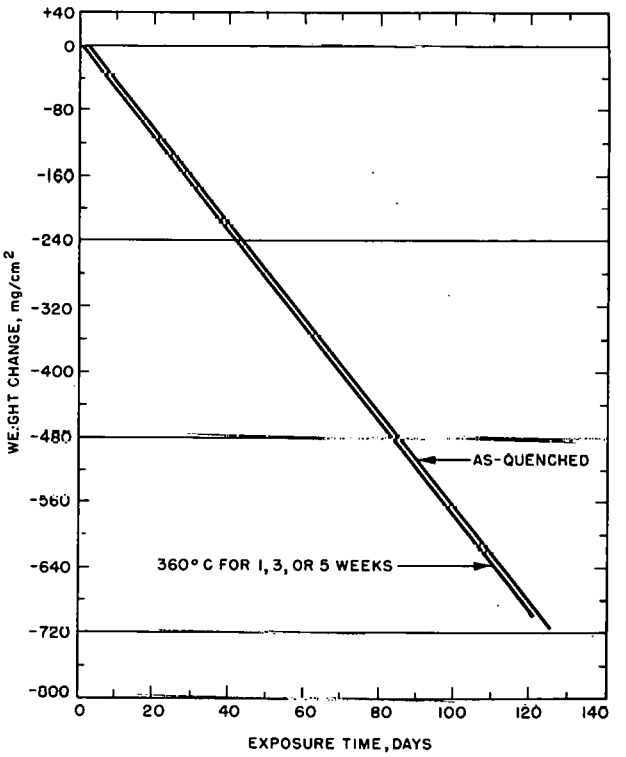


Fig. 24 360°C Water Corrosion of Zirconium + 50 w/o Uranium; Quenched from 850°C, Subsequently Annealed at 360°C, and Slowly Cooled

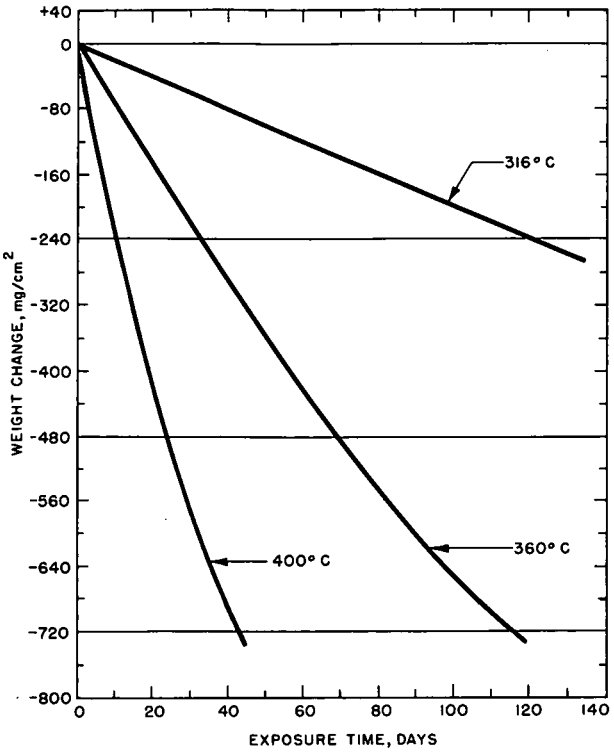


Fig. 25 Effect of Temperature on the Corrosion of Zirconium + 50 w/o Uranium; Samples Slowly Cooled from 575°C

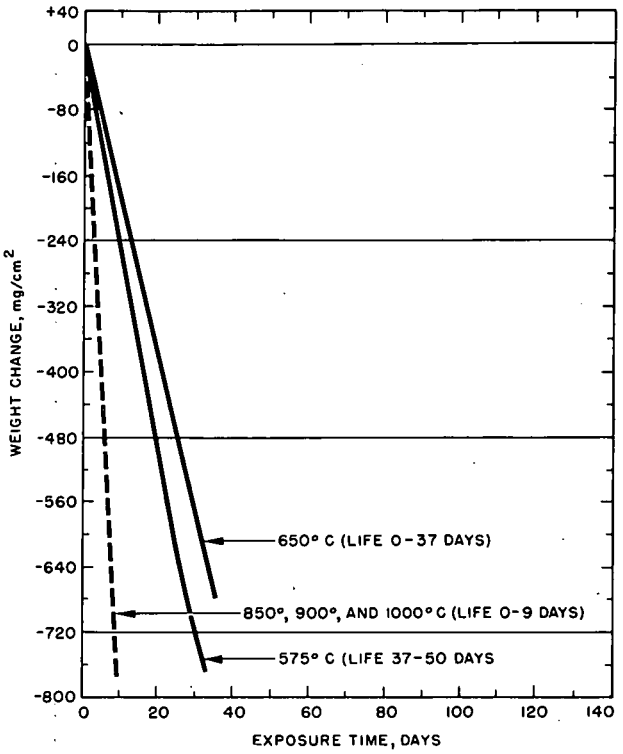


Fig. 26 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 60 w/o Uranium; Samples Quenched from Temperature

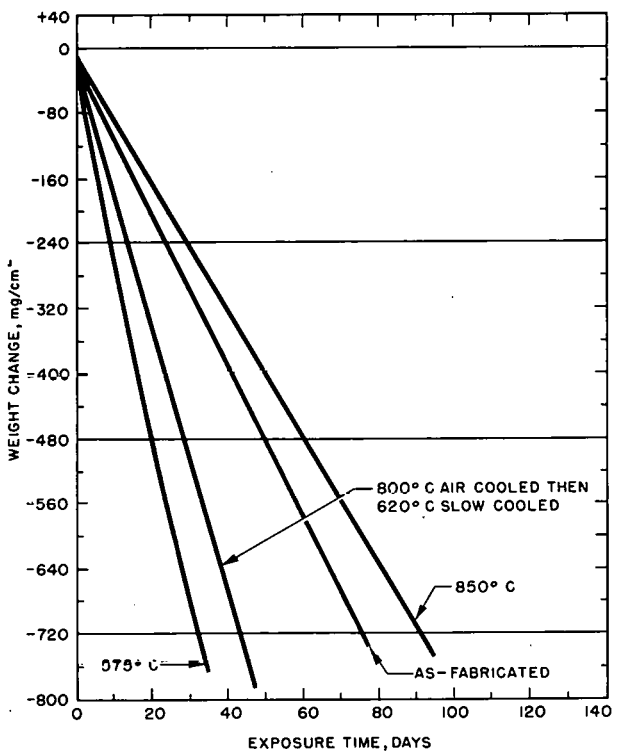


Fig. 27 Effect of Temperature on the 360°C Water Corrosion Behavior of Zirconium + 60 w/o Uranium; Samples Slowly Cooled from Temperature

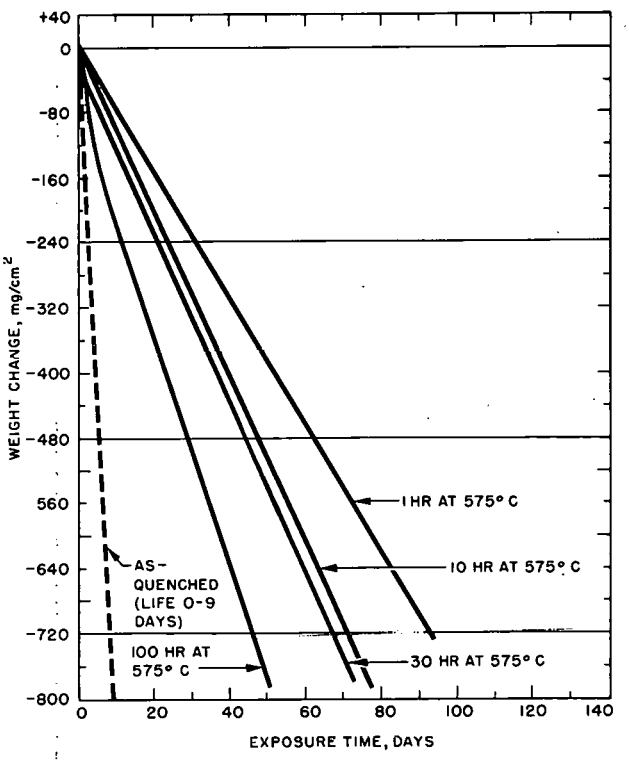


Fig. 28 360°C Water Corrosion of Zirconium + 60 w/o Uranium; Quenched from 850°C, Subsequently Annealed at 575°C, and Slowly Cooled

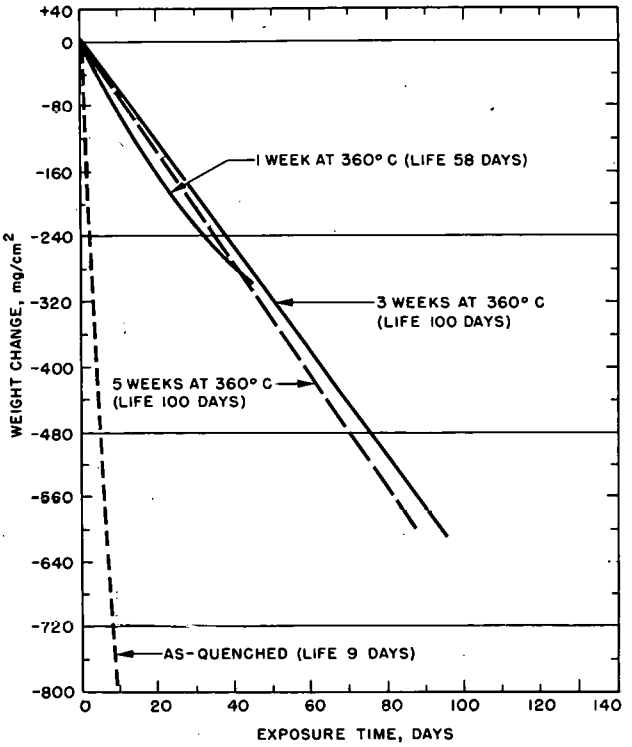


Fig. 29 360°C Water Corrosion of Zirconium + 60 w/o Uranium; Quenched from 850°C, Subsequently Annealed at 360°C, and Slowly Cooled

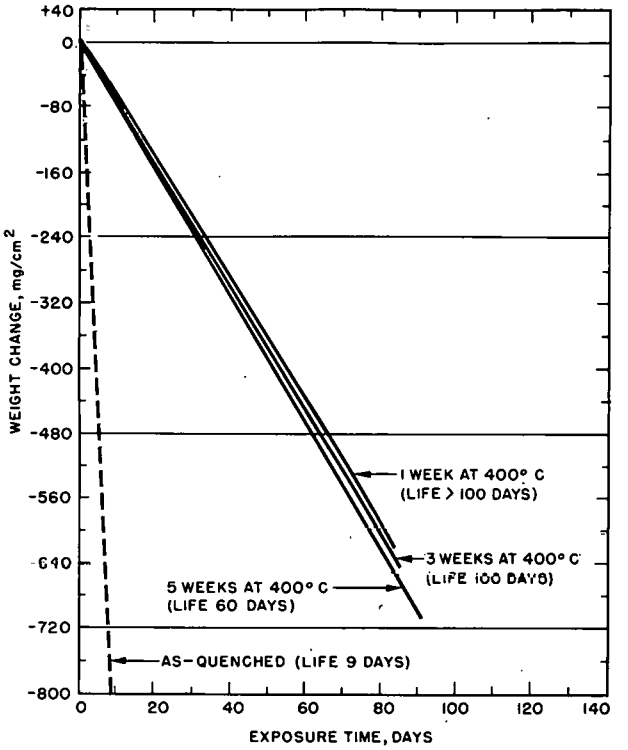


Fig. 30 360°C Water Corrosion of Zirconium + 60 w/o Uranium; Quenched from 850°C, Subsequently Annealed at 400°C, and Slowly Cooled

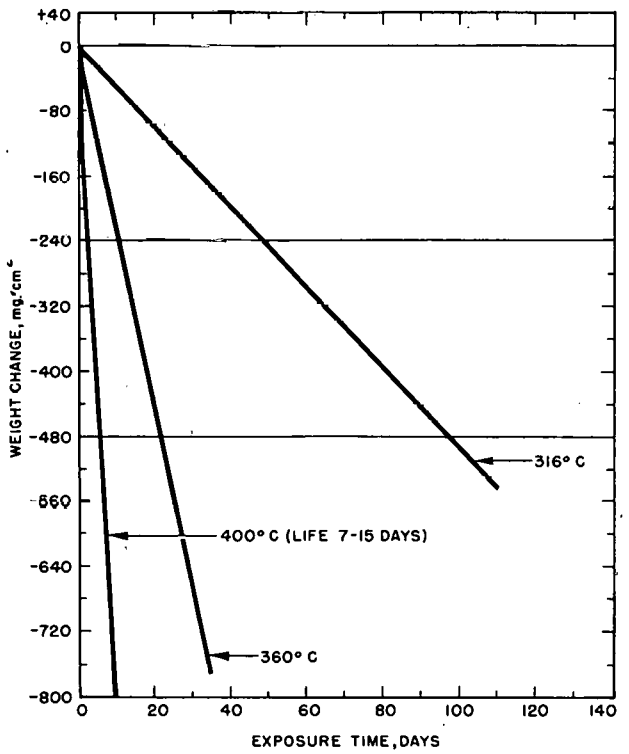


Fig. 31 Effect of Temperature on the Corrosion of Zirconium + 60 w/o Uranium; Samples Slowly Cooled from 575°C

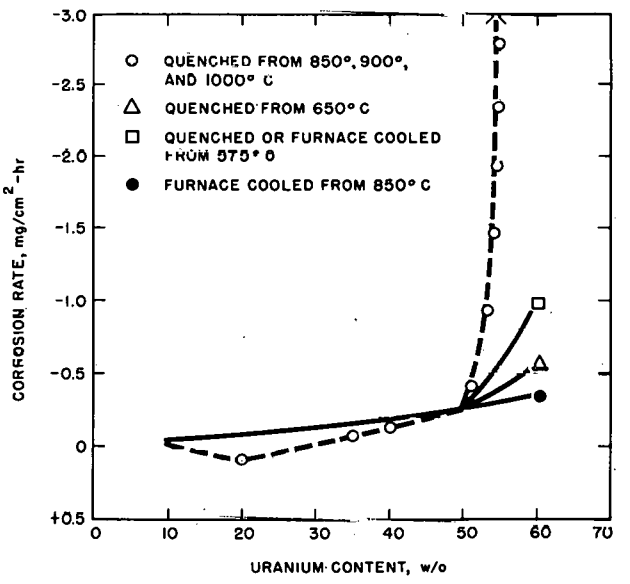


Fig. 32 360°C Water Corrosion of Zirconium-Uranium Alloys

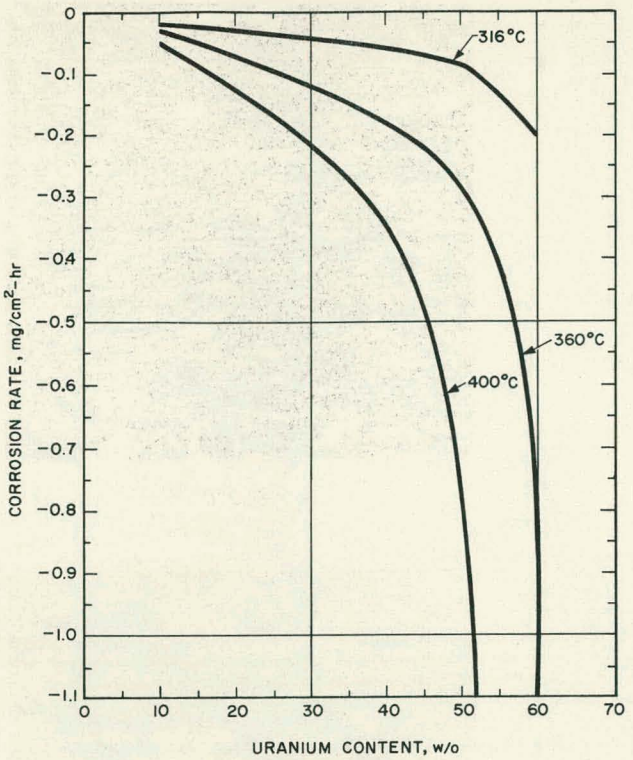


Fig. 33 Effect of Test Temperature on the Corrosion of Zirconium-Uranium Alloys; Samples Slowly Cooled from 575°C

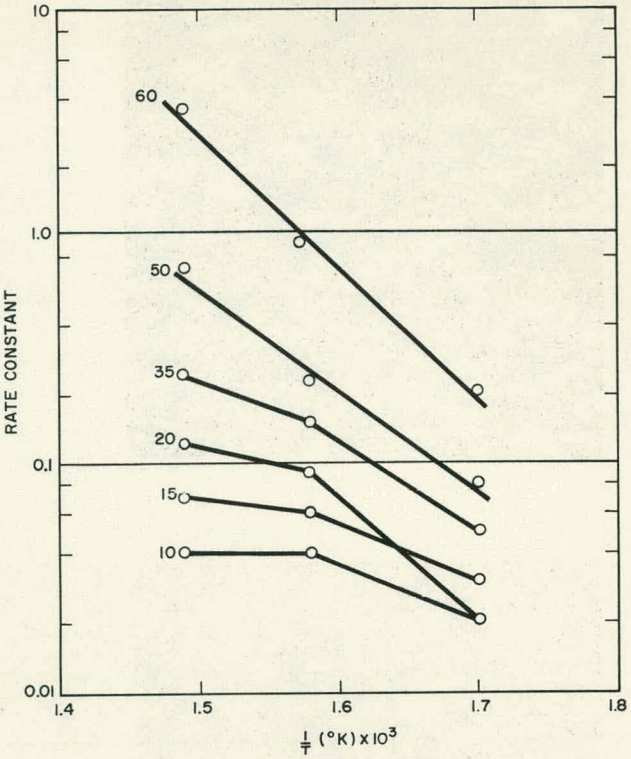


Fig. 34 Effect of Temperature on the Corrosion Rate of Zirconium-Uranium Alloys

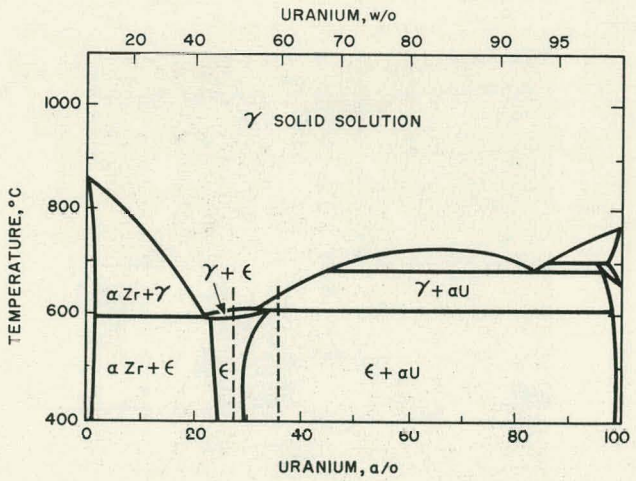
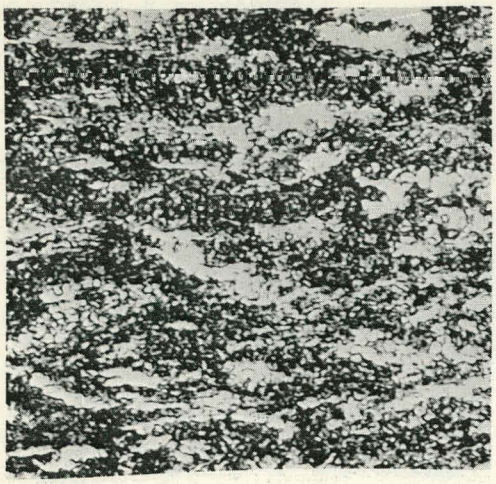
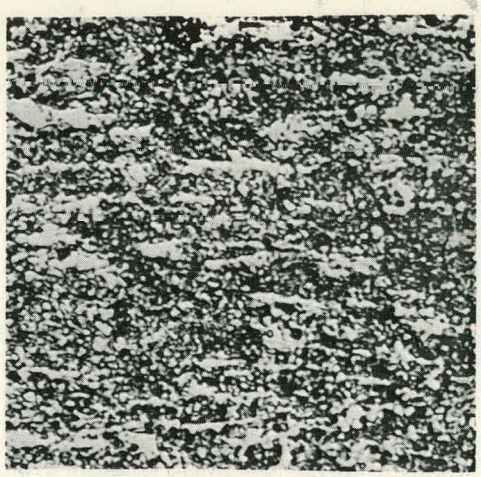


Fig. 35 Phase Diagram of the Zirconium-Uranium System



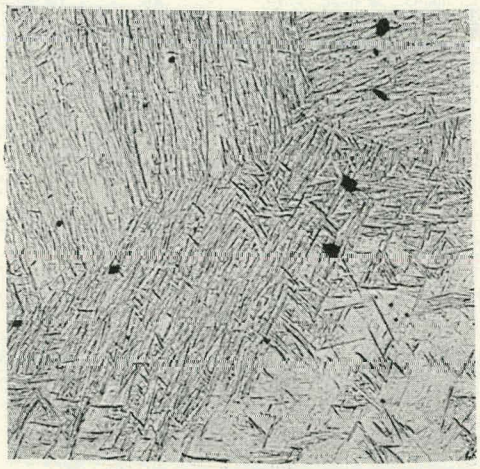
575°C



650°C

850°C

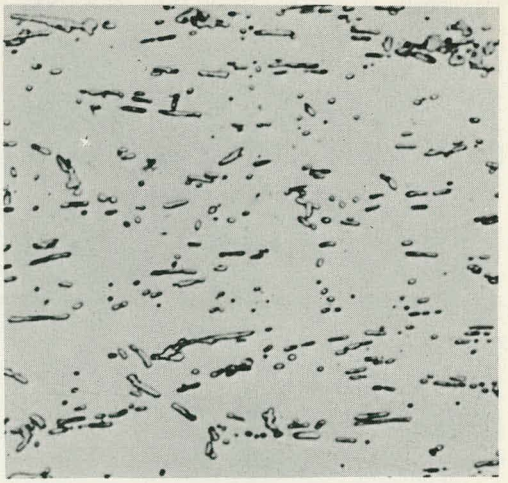
900°C



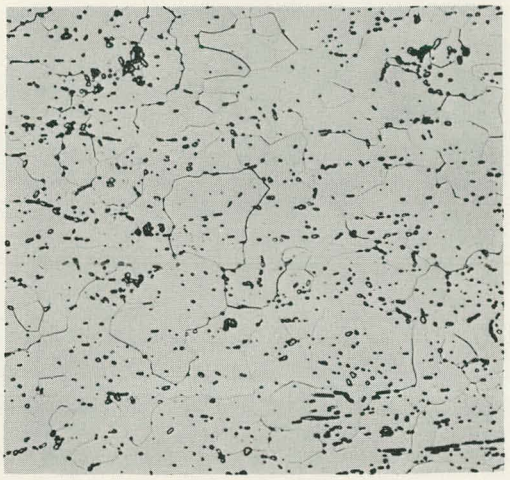
1000°C

Fig. 36 Typical Microstructures of Quenched Zirconium + 10 w/o Uranium Alloys; All 250X

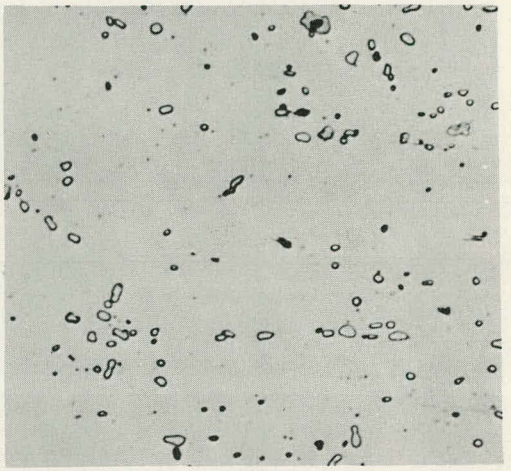
575°C



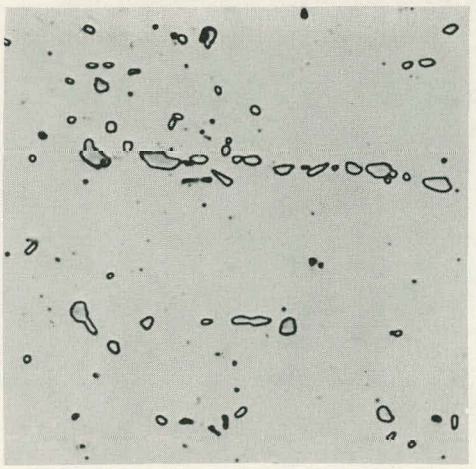
650°C



850°C

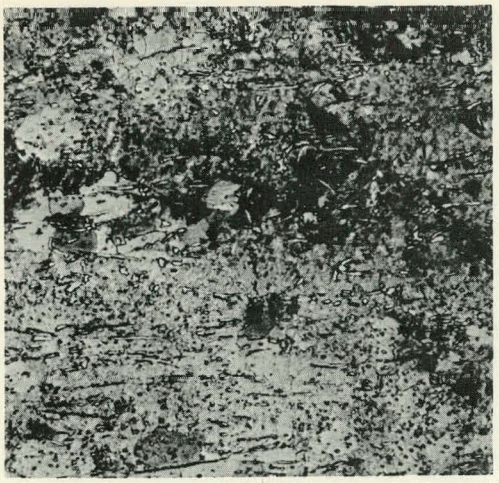


900°C

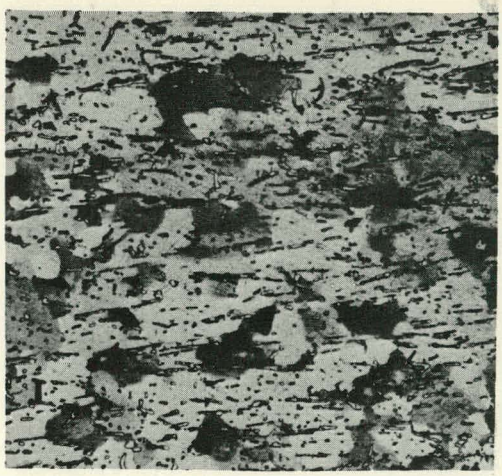


1000°C

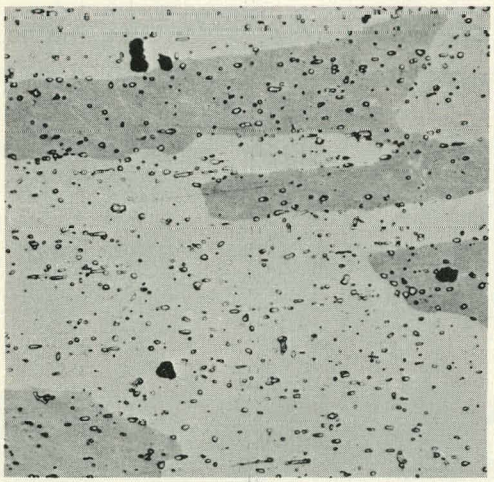
Fig. 37 Typical Microstructures of Quenched Zirconium + 50 w/o Uranium Alloys; All 250X



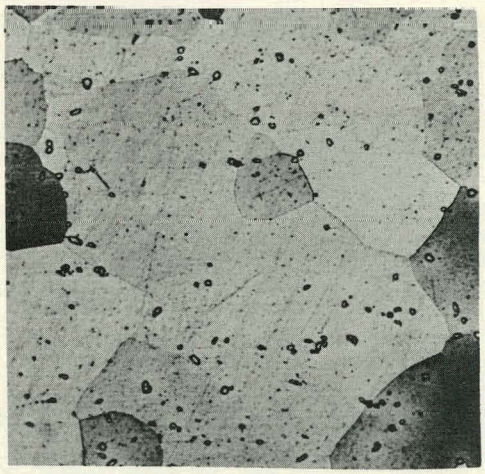
575°C; 500X



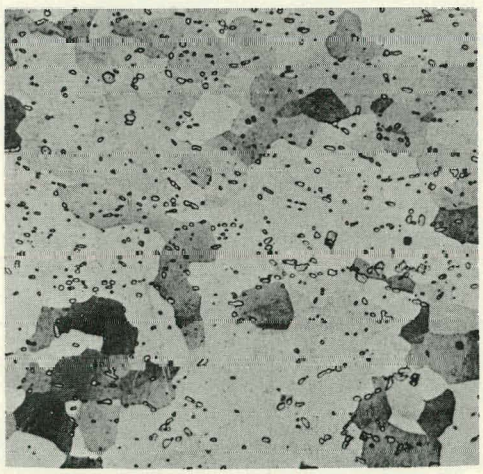
650°C; 500X



850°C; 250X



900°C; 500X



1000°C; 500X

Fig. 38 Typical Microstructures of Quenched Zirconium + 60 w/o Uranium Alloys