MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES
3 4456 0361540 7

CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION

ORNL-2995
UC-25 - Metallurgy and Ceramics

A PRELIMINARY STUDY OF THE AGING BEHAVIOR OF WROUGHT COLUMBIUM-1% ZIRCONIUM ALLOYS

D. O. Hobson

CENTRAL RESEARCH LIBRARY
DOCUMENT COLLECTION
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this document, send in name with document and the library will arrange a loan.

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

ORNL-2995

METALLURGY DIVISION

Contract No. W-7405-eng-26

A PRELIMINARY STUDY OF THE AGING BEHAVIOR OF WROUGHT COLUMBIUM-1% ZIRCONIUM ALLOYS

David O. Hobson

DATE ISSUED

JAN 6 1961

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

MARTIN MARIETTA ENERGY SYSTEMS LIBRARIES

3 4456 0361540 7

A PRELIMINARY STUDY OF THE AGING BEHAVIOR OF WROUGHT COLUMBIUM-1% ZIRCONIUM ALLOYS

ABSTRACT

The aging behavior of nine commercial heats of Cb-nominal 1 wt % Zr alloys was determined at 816°C (1500°F) and 927°C (1700°F) for periods up to 750 hr through the use of tensile and hardness tests. Several, but not all, of the alloys responded to heat treatment. It was found that the aging phenomena were influenced by the preage annealing temperature as well as the impurity content of the alloys. Higher annealing temperatures led to more pronounced aging effects. It was found also that the aging or nonaging behavior of the alloys could be correlated with their oxygen-nitrogen ratios and to a lesser extent with their oxygen-carbon ratios. There was a positive correlation between the amount of oxygen added to the alloy and the tendency for aging to occur. When sufficient oxygen was added, the aging tendency could be virtually eliminated. No correlation was found between observed aging effects and surface contamination.

INTRODUCTION

The solubility of oxygen, carbon, and nitrogen in columbium decreases with decreasing temperature, and therefore, the presence of these impurities in the metal suggests the possibility of aging phenomena. Moreover, these impurities in the presence of zirconium as an alloying element would probably precipitate oxides, carbides, or nitrides of zirconium in preference to those of columbium, since thermodynamics favor their formation. It is, therefore, possible that certain combinations of the above elements will have a significant effect on the mechanical properties of the alloys when the amounts present exceed the solubility limits.

In the course of the investigation of columbium-base alloys, it was discovered that a Cb-1% Zr alloy which was held at 927°C for 500 hr in an argon-filled container exhibited significantly increased strength and decreased ductility. As a result of this experiment, a series of experiments at varying aging times and temperatures was conducted.

This report summarizes the work completed to date.

EXPERIMENTAL PROCEDURE

All tensile specimens used in the aging studies were stamped to size from 0.040-in.-sheet stock. The specimens had a 2-in.-gage length with a 0.25-in. x 0.040-in. cross section. After stamping, the specimens were vacuum annealed for 2 hr at temperatures ranging from 1200°C (2192°F) to 1600°C (2912°F). The annealing was done in a resistance-heated, tantalum-element furnace under a vacuum of approx 1×10^{-5} mm Hg. After annealing, the specimens were encapsulated in quartz tubes under a vacuum of approx 5×10^{-6} mm Hg. During evacuation, the tubes were heated with a hand torch to ensure complete outgassing. The capsules, after sealing, were placed in furnaces at temperatures of 816°C and 927°C and aged from 25 to 750 hr. After aging, the capsules were quenched in water and then broken when cool.

To determine the effect of oxygen on the aging behavior of the Cb–1% Zr alloy, two heats, PGVE and S23SC-1, were contaminated with low levels of oxygen using a modified Sievert's apparatus. A dynamic system was used in which dried, high-purity oxygen at a pressure of 1×10^{-4} mm Hg was bled into the reaction tube at 1000°C (1832°F). Specimens were held at these conditions for 30 min to 2 hr, depending on the amount of contamination desired. After the oxygen was introduced, the specimens were homogenized at 1600°C for 2 hr, then aged as described above.

Early tensile tests were conducted on step-loaded creep frames. However, these had the disadvantages of a nonuniform strain rate and the inability to record an accurate yield point. Later tests were conducted on a Baldwin hydraulic testing machine, using 1/4-in.-pin grips and a cross-head speed of 0.005 in./min. Duplicate specimens were run on both the creep frame and the tensile machine. Good agreement was obtained for the ultimate tensile strength and ductility of duplicate specimens on both pieces of equipment.

The test chamber for high-temperature tensile testing consisted of a 2-in., sched-40, Inconel tube with water-cooled end caps. Rubber U-caps were used to seal the pullrods and the chamber was heated by a Marshall high-temperature furnace. By using a mechanical pump and diffusion pump, it was possible to obtain vacuums of the order of 1.5×10^{-4} to 5×10^{-5} mm Hg in the test chamber.

After the tests were completed, the specimen elongation was measured by butting the fractured ends together and measuring the total change in the length of the gage section.

Hardness measurements were made with a Kentron hardness tester with a diamond pyramid indenter and 500-g load. At least six impressions were made for each reported point.

RESULTS

Aging Results

Initial aging studies were conducted on two heats of columbium-zirconium alloys, a Cb–1.0% Zr alloy (S4KW) from Kennametal, Incorporated, and a Cb–0.75% Zr alloy (S8FW) from Fansteel Metallurgical Corporation. All specimens were vacuum annealed for 2 hr at 1600°C before aging.

The results of the room-temperature tensile tests are shown in Fig. 1. The Cb–0.75% Zr alloy aged at 816°C for 25, 50, and 100 hr was weaker than the same alloy aged at 927°C for the same times. However, after 100 hr the strength of the alloy aged at 816°C increased and surpassed the strength of the alloy aged at 927°C which had begun to overage. The strength of the alloy aged at 816°C reached a maximum after approx 750 hr. The Cb–1.0% Zr alloy was strongest after approx 175 hr at 927°C. There was a general loss in ductility with increasing aging time in both alloys.

Figure 2 shows the results of the high-temperature tensile tests on the aged Cb–1.0% Zr and Cb–0.75% Zr alloys. The curves are essentially the same as the room-temperature tests except the aging response was much more drastic. The Cb–0.75% Zr alloy aged and tested at 816°C showed a rapid increase in strength after 75 hr and it was still increasing after 750 hr. There was a noticeable loss in ductility with aging time and when compared with the room-temperature tests.

Figure 3 shows the hardnesses of the Cb–0.75% Zr alloy as a function of aging time. Note that the shapes of the curves correspond to those of the tensile-test curves.

Studies were continued with another heat of commercial columbium-zirconium alloy which had been electron-beam melted and then double arc-melted. This alloy (PFYU) contained 1.15% Zr. Three sets of tensile specimens of this alloy were annealed for 2 hr at 1200°C, 1400°C (2552°F), and 1600°C. These specimens were aged at 927°C and then tensile tested at

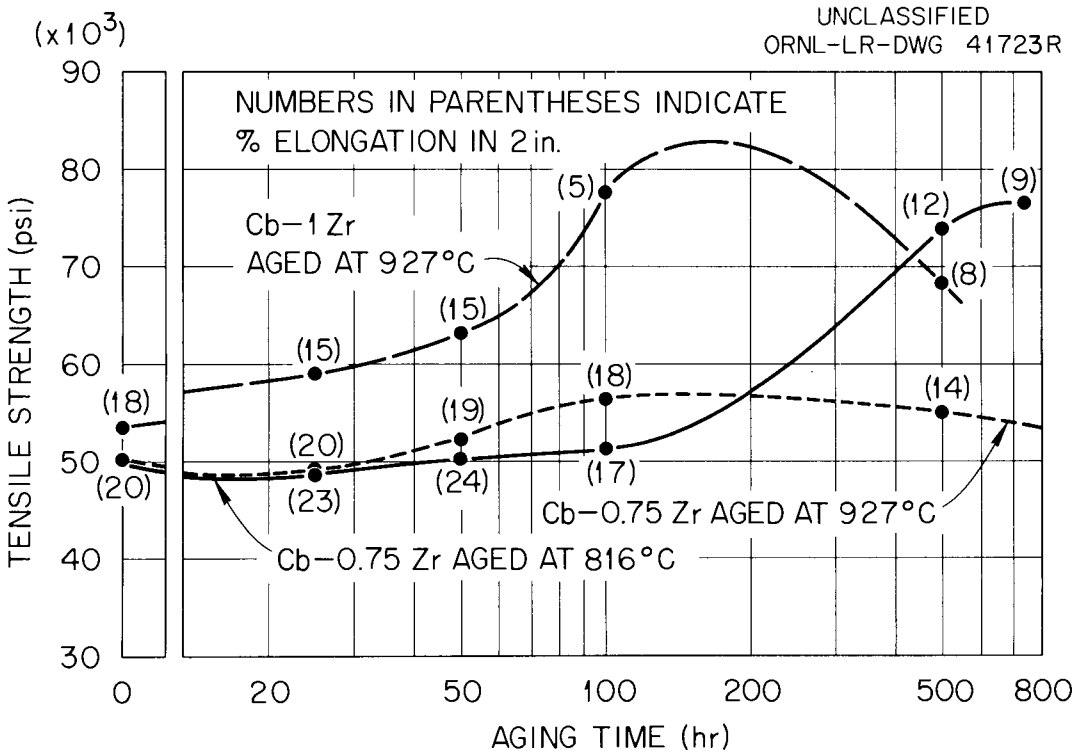

Fig. 1 Room Temperature Tensile Tests on Two Aged Cb-Zr Alloys.

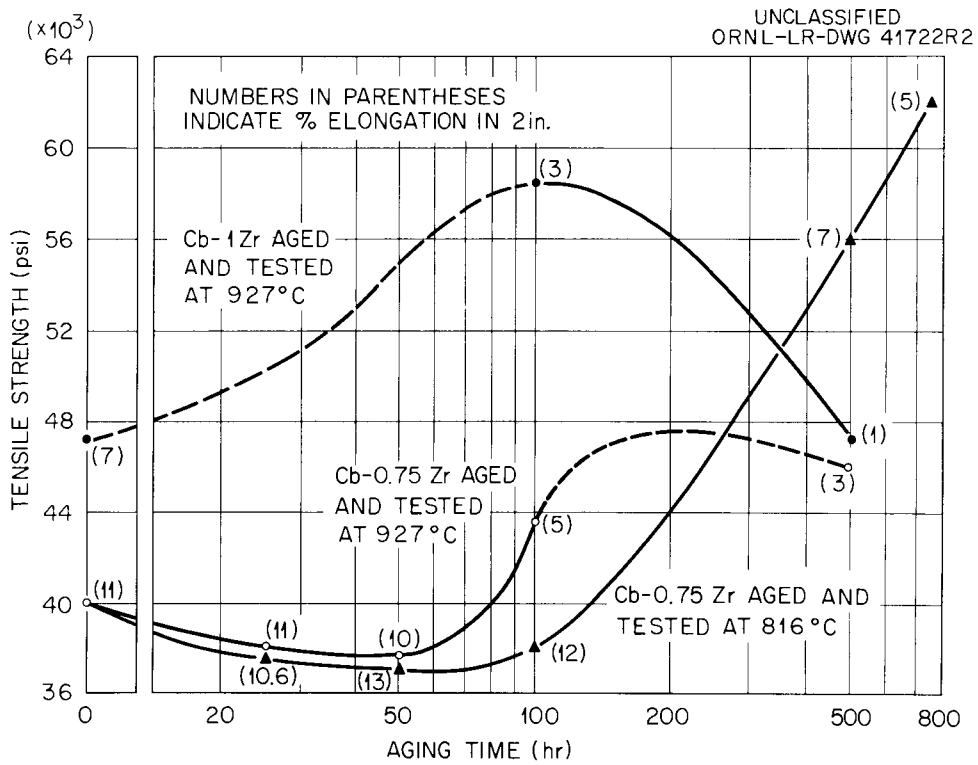

Fig. 2 High-Temperature Tensile Tests on Two Aged Cb-Zr Alloys.

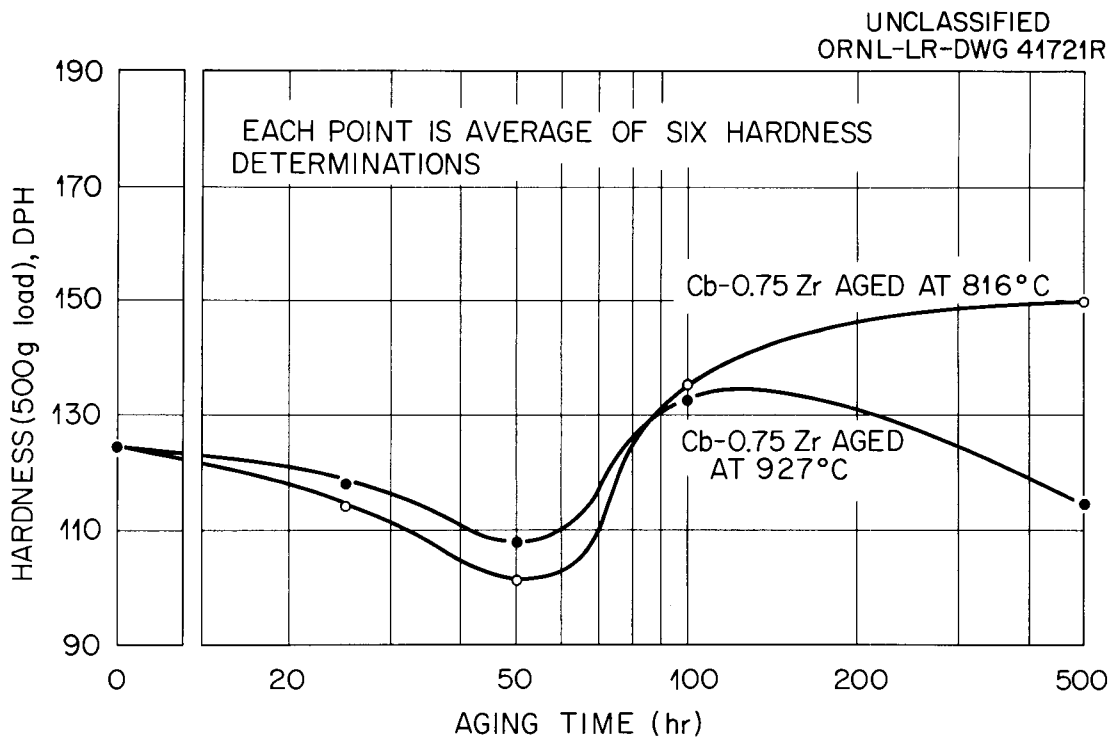

Fig. 3 Hardnesses of Cb–0.75% Zr Alloy Aged at 816°C and 927°C.

927°C. The results of these tests are shown in Fig. 4. These data indicate that a 1600°C solution anneal causes a greater aging effect than either the 1200 or 1400°C anneal. This is presumably due to more material being taken into solution at the higher annealing temperatures. In all cases there was a reduction of elongation with increasing aging time.

Figures 5 through 9 show the microstructures of the Cb–1.15% Zr alloy (PFYU) aged and tested at 927°C after annealing at 1600°C.

Figure 5 shows the as-annealed microstructure. There is some precipitate present in the matrix which may have been formed due to too slow a cooling rate after annealing. The specimens cooled very rapidly by radiation to below red heat when the water-cooled resistance furnace was turned off. However, to cool from red heat, approx 700°C, to room temperature took from 30 to 60 min depending on the charge size.

Figure 6 shows the microstructure of a specimen aged 50 hr at 927°C and tested at 927°C. Some precipitate is present in the grain boundaries of the specimen. However, the matrix precipitate seen in the as-annealed specimen is absent. This is possibly due to the 927°C aging and testing temperature being sufficiently high to put the precipitate back into solid solution. Then, upon quenching, the phase was unable to reprecipitate.

Figure 7 shows the microstructure of a specimen aged 100 hr at 927°C. Again, some precipitate is present in the grain boundaries. Precipitation is also taking place in the matrix.

Figure 8 shows a specimen after aging 200 hr at 927°C. The matrix precipitate has coarsened and some areas around the grain boundaries have become depleted. There is some evidence of a continuous grain boundary phase.

Figure 9 shows a specimen after aging 500 hr at 927°C. The matrix precipitate has continued to coarsen and there is further depletion of the matrix adjacent to the grain boundaries. The grain boundaries show an almost continuous phase.

In this series, all specimens were prepared in the same mount, and hence, received the same polishing and etching procedure.

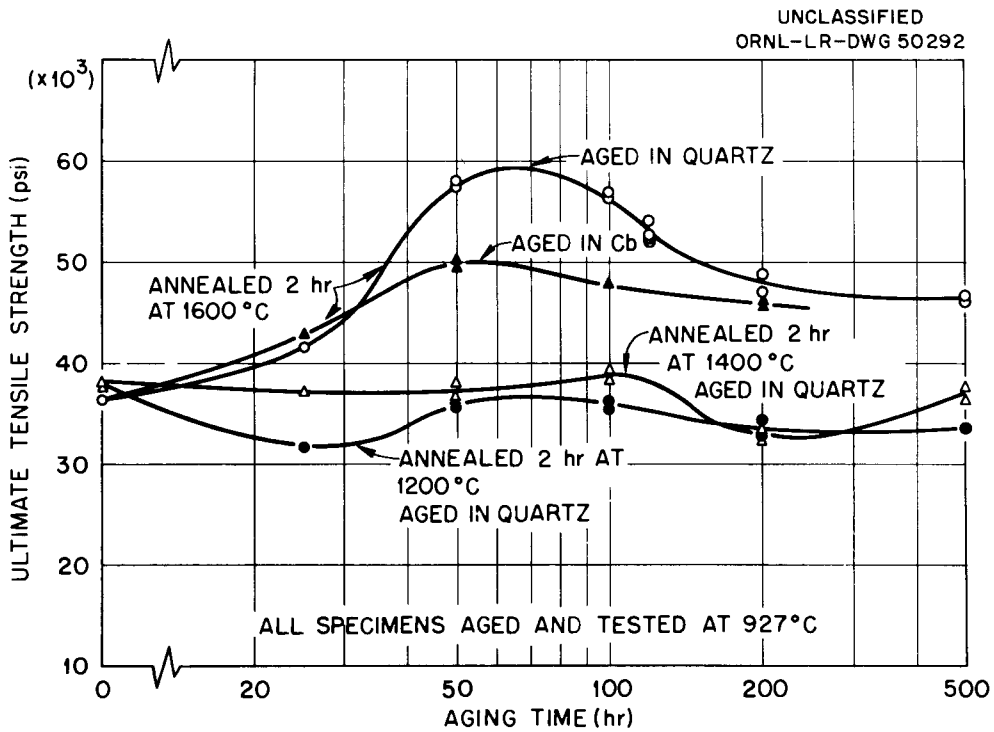

Fig. 4 Effect of Annealing Temperature and Aging Container on the Aging Phenomena in Cb–1% Zr Alloy (PFYU).

Fig. 5 Microstructure of Cb–1.15% Zr Alloy, As Annealed. Etchant: 50 H_2O–25 HNO_3–10 HF–10 H_2SO_4.

Fig. 6 Microstructure of Cb–1.15% Zr Alloy Aged 50 hr at 927°C. Etchant: 50 H_2O–25 HNO_3–10 HF–10 H_2SO_4.

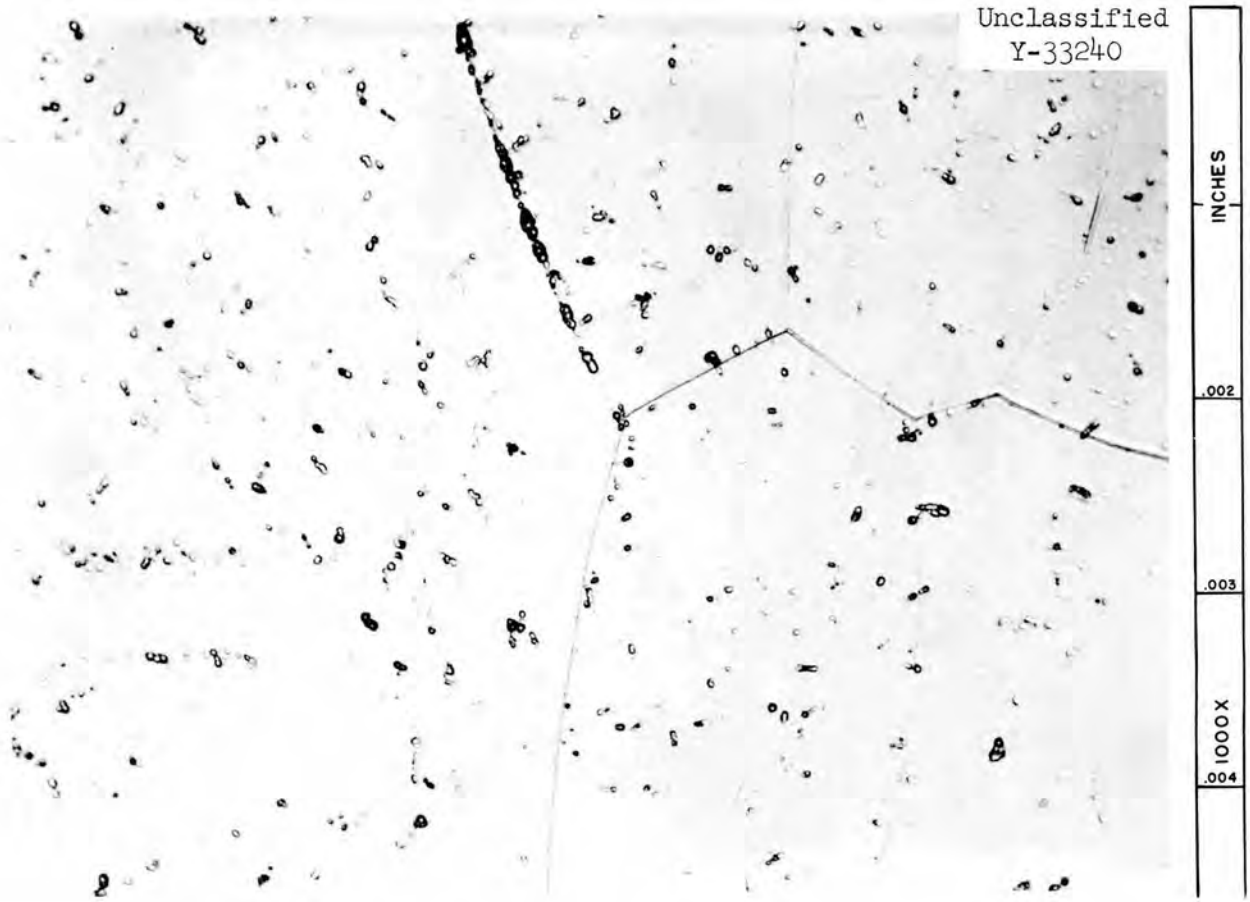

Fig 7 Microstructure of Cb–1.15% Zr Alloy Aged 100 hr at 927°C. Etchant: 50 H_2O–25 HNO_3–10 HF–10 H_2SO_4.

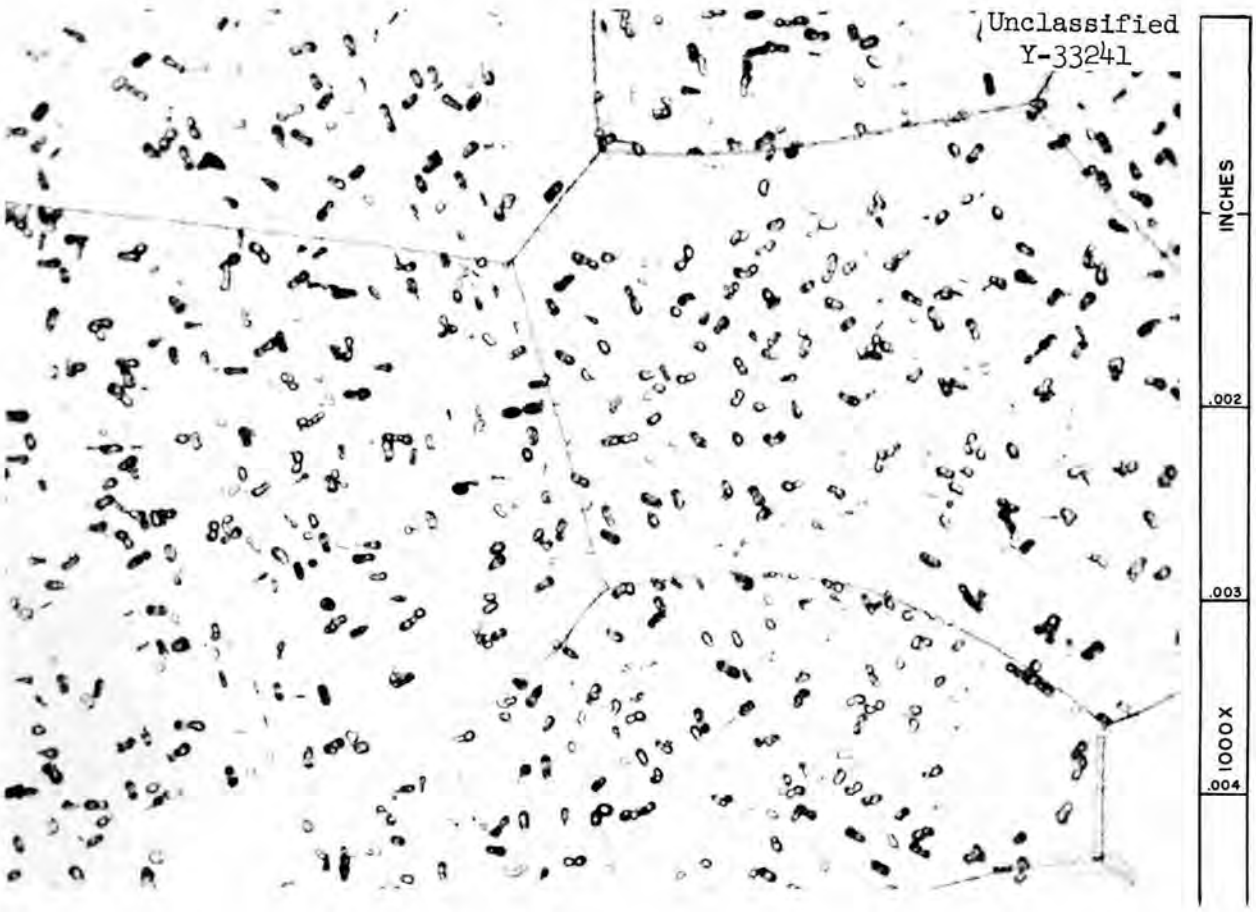

Fig. 8 Microstructure of Cb–1.15% Zr Alloy Aged 200 hr at 927°C. Etchant: 50 H_2O–25 HNO_3–10 HF–10 H_2SO_4.

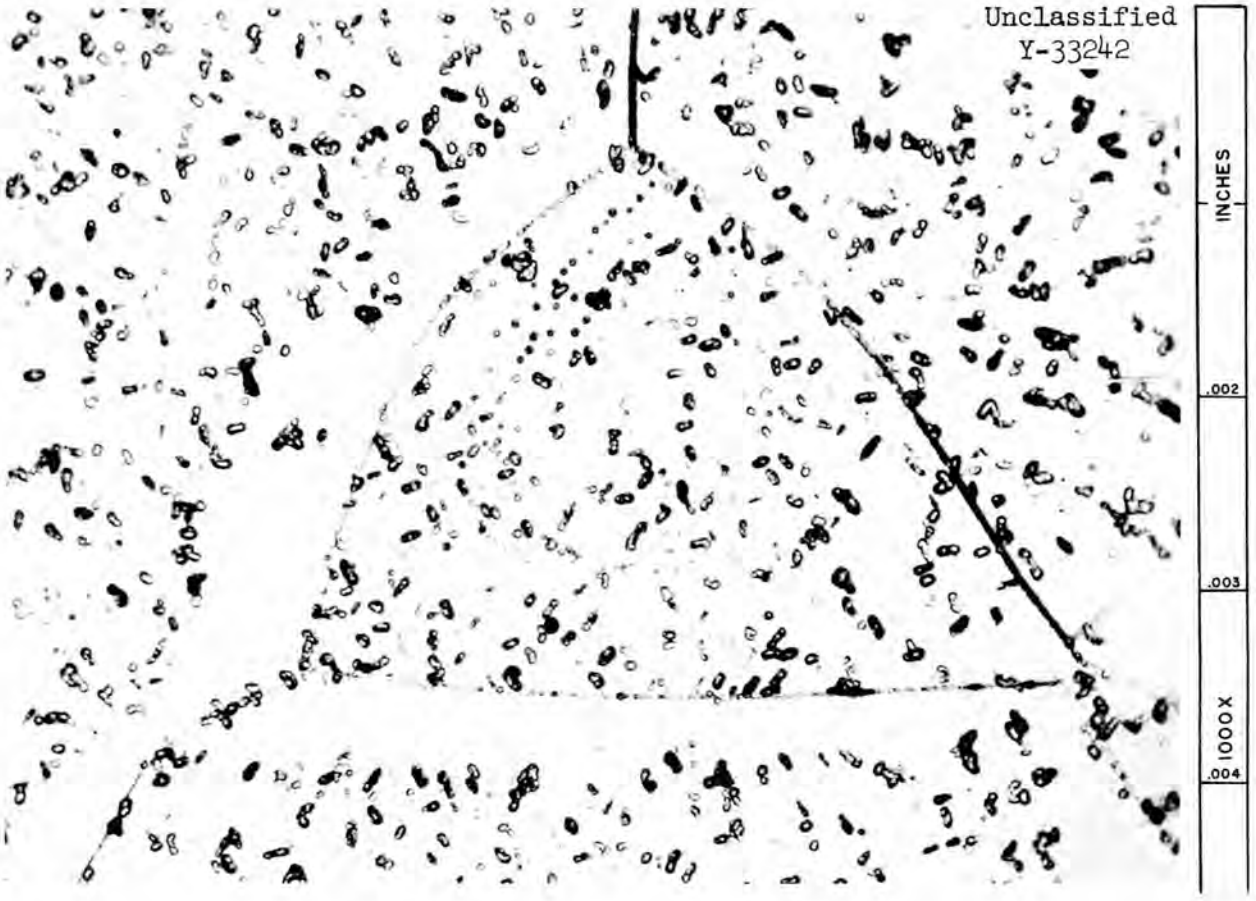

Fig 9 Microstructure of Cb-1.15% Zr Alloy Aged 500hr at 927°C. Etchant: 50 H_2O-25 HNO_3-10 HF-10 H_2SO_4.

Effects of Surface Contamination

Following the compilation of the foregoing data, the question arose concerning the role of surface contamination on the strength and ductility changes of the alloys. In an effort to determine the effect of surface contamination, several experiments were performed.

Three heats of Cb–1% Zr alloy (PFYU, PGTF, and PGVE) were used to test the effect of machining off the outer layers of the tensile specimens after aging. Two 0.040-in.-thick and two 0.045-in.-thick specimens were stamped from sheets of each heat. These were vacuum annealed for 2 hr at 1600°C and then aged in quartz for 120 hr at 927°C. The 0.045-in. specimens were then machined on both sides to 0.040 in. All specimens were tensile tested at 927°C. The results are given in Table 1. The machined specimens of heats PFYU and PGVE showed a slight decrease in tensile strength, while the tensile strength of heat PGTF did not change as a result of machining. However, in heats PFYU and PGVE the as-aged ultimate tensile strength was still significantly higher than when the heat was in the as-annealed condition. Only heat PFYU showed an increase in elongation as a result of machining.

Other specimens of heat PFYU were sealed in argon-filled columbium capsules which were in turn sealed in argon-filled stainless steel capsules. All welding was done in a controlled atmosphere chamber. The specimens were aged and tested at 927°C. The results are shown in Fig. 4. It can be seen that aging has less effect on the mechanical properties of the specimens aged in columbium than on those aged in quartz. The reason for this is not presently known.

A special heat of Cb–1.25% Zr alloy (S23SC-1) which contained less than 350 ppm total interstitial concentration, was annealed for 2 hr at 1600°C and then aged under three different conditions. Two specimens were aged in an argon-filled columbium capsule, two were aged in an evacuated quartz capsule, and two specimens were wrapped in tantalum foil before aging in an evacuated quartz capsule. All specimens were aged 100 hr at 927°C and then tensile tested at 927°C. The results are shown in Table 2.

Table 1. Surface Effects on Tensile Properties of Aged Columbium-Zirconium Alloys

Heat No.	Condition[a]	Ultimate Tensile Strength (psi)	Yield Strength (psi)	% Elongation in 2-in.-gage length
PFYU	As annealed	36 400	-	11
PFYU	Aged, unmachined	52 000	-	-
PFYU	Aged, unmachined	54 000	-	-
PFYU	Aged, machined	46 520	44 680	9.5
PFYU	Aged, machined	47 680	46 470	10
PGTF	As annealed	35 500	25 640	10
PGTF	Aged, unmachined	30 920	14 890	14
PGTF	Aged, unmachined	30 610	17 165	14
PGTF	Aged, machined	29 740	19 355	12
PGTF	Aged, machined	30 745	21 975	11
PGVE	As annealed	24 610	10 445	8
PGVE	Aged, unmachined	36 200	30 785	5
PGVE	Aged, unmachined	36 200	31 315	6.5
PGVE	Aged, machined	33 065	25 605	7
PGVE	Aged, machined	33 092	25 855	6

[a]All specimens annealed 2 hr at 1600°C. Aged specimens were heat-treated 120 hr at 927°C in evacuated quartz capsules. All specimens tensile tested at 927°C.

Table 2. Effect of Various Containers on the Aging of a Cb–1.25% Zr Alloy

Condition	Ultimate Tensile Strength (psi)	Yield Strength (psi)	% Elongation (2 in.)	% Elongation (2-1/2 in.)
Annealed 2 hr at 1600°C	24 945	11 464	12	9.5
Annealed 2 hr at 1600°C	25 390	14 270	8.5	7
Aged 100 hr at 927°C in argon-filled Cb capsule	34 870	33 095	4.5	4.5
Aged 100 hr at 927°C in argon-filled Cb capsule	32 165	28 980	4	2.5
Aged 100 hr at 927°C in quartz capsule	39 980	38 940	4	3
Aged 100 hr at 927°C in quartz capsule	33 715	30 505	5	4.5
Aged 100 hr at 927°C tantalum-wrapped in quartz	38 960	36 645	5	4
Aged 100 hr at 927°C tantalum-wrapped in quartz	33 920	31 415	3.5	3

While it is evident that there are slight differences in the strengths and elongations among the specimens aged in the three different containers, note that the strengths are from 33 to 65% higher and the ductilities are from 50 to 65% lower than the as-annealed material.

As a further check for the effect of surface contamination, one set of specimens from heat PGVE was annealed 2 hr at 1600°C. The specimens were wrapped in tantalum foil, sealed in evacuated quartz capsules, and aged as before. These specimens were then tensile tested at 927°C. The results are shown in Fig. 10 and indicate that the alloy has a definite aging response. These results show good agreement with the data on heat PGVE presented in Table 1.

Limited aging tests were run on three other Cb–1% Zr alloys (S24EW, S15EC, and S16EC). These tests were sufficient to determine that these alloys did not age.

DISCUSSION

A total of nine different heats of Cb–nominal 1% Zr alloy has been tested for aging effects. Table 3 lists the alloys with their starting chemical analyses and whether they did or did not exhibit aging.

On comparing the chemical analyses of the different heats, it was observed by J. R. DiStefano that the heats which had a relatively high oxygen content did not exhibit aging. On the basis of this observation it is postulated that the presence of oxygen had an inhibiting effect on the aging response of the alloys. No correlation has been observed between the aging effect and any single element other than oxygen. However, correlation can be obtained when the various oxygen, carbon, and nitrogen contents are listed as ratios of oxygen/carbon and oxygen/nitrogen.

It is believed that a zirconium compound, either zirconium nitride or zirconium carbide, precipitates at the aging temperature to cause the observed aging effect and that oxygen acts as an inhibitor of the aging reaction. The free energy of formation data and diffusion rate constants favor the preferential formation of zirconium oxide over either zirconium nitride, zirconium carbide, or columbium oxide, carbide, or nitride.

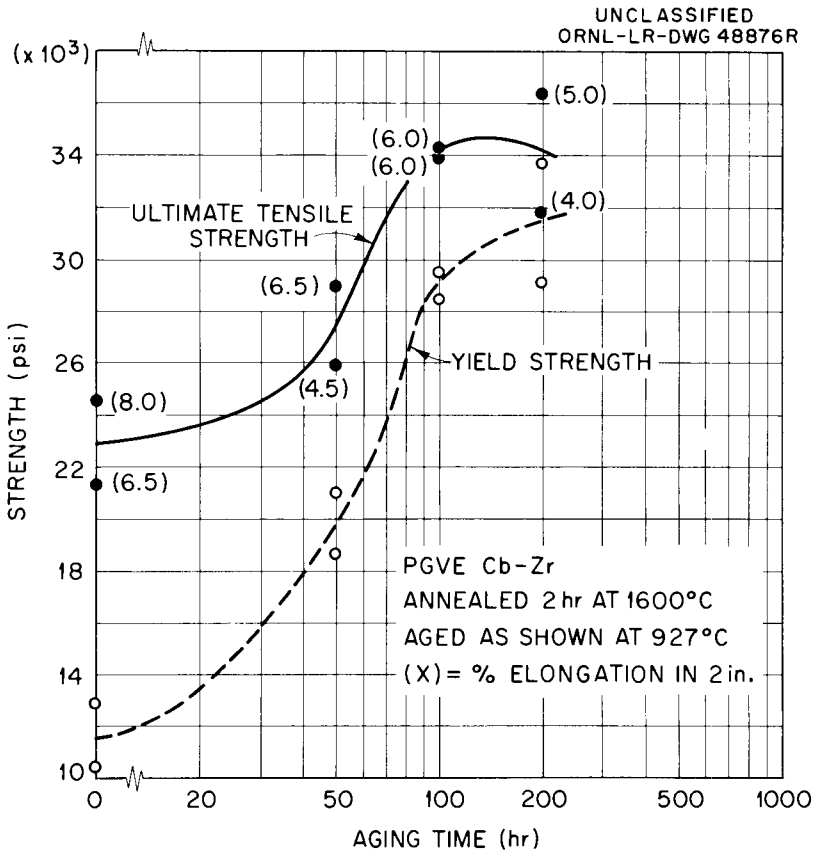

Fig. 10 High-Temperature Tensile Tests of Cb–1% Zr Alloy (PGVE).

Table 3. Chemical Analyses of Aged Columbium-Zirconium Alloys[a]

Heat No.	O_2 (ppm)	N_2 (ppm)	C (ppm)	Zr (wt %)	O_2/C	O_2/N_2	Remarks
PFYU	145	160	210	1.07	0.7	0.9	Definite aging
PGVE	106	115	120	0.98	0.9	0.9	Definite aging
S4KW	200	200	300	1.0	0.7	1.0	Definite aging
S23SC-1	120	85	140	1.25	0.9	1.4	Definite aging
S8FW	260	160	70	0.75	3.7	1.6	Definite aging
S15EC	900	140	170	0.76	5.3	6.4	No aging
PGTF	320	46	120	1.14	2.7	7.0	No aging
S16EC-1	1300	180	190	0.60	6.8	7.2	No aging
S24EW	900	100	500	0.77	1.8	9.0	No aging

[a]Specimens annealed at 1600°C for 1 hr and aged at 927°C.

In an effort to further correlate the effects of O_2, N_2, C, and Zr in the alloys, plots were made of O_2/Zr vs N_2/Zr and O_2/Zr vs C/Zr. The plot for O_2/Zr vs N_2/Zr is shown in Fig. 11. It can be seen that the alloys fall into two different regions of the graph according to whether they did or did not age. The plot of O_2/Zr vs C/Zr follows the same pattern except for heat S8FW. If it is assumed that this hypothesis is correct, then it should be possible to add oxygen to the heats which exhibit aging and cause a decrease in the aging effect. This would have the effect of moving the alloy from an aging to a nonaging region of the graph.

To test this theory, several oxygen additions were made to heats PGVE and S23SC-1, both of which had exhibited aging. After oxygen contamination, the specimens of each heat were homogenized for 2 hr at 1600°C. These specimens were then tensile tested at 927°C in the annealed condition and following a 100-hr age at 927°C.

Table 4 and Fig. 12 illustrate the changes in the tensile properties with the addition of oxygen to the alloys. It should be noticed that the difference between the yield strengths of the as-annealed and as-aged specimens shows a drastic decrease with increasing oxygen content. The elongations of the annealed specimens and the aged specimens tend to approach a common percentage elongation with increasing oxygen content. The uncontaminated as-annealed specimens had a fairly high elongation which decreased slightly with increasing oxygen content, and the uncontaminated, as-aged specimens had a low initial elongation which increased with increasing oxygen content.

The oxygen contents shown in the table and in the figures are the as-added values of oxygen. These values were calculated from weight change data after contamination. Chemical analyses made after heat treating and testing showed that the specimens lost approximately half of their contained oxygen and carbon, probably during the high-temperature anneal as carbon monoxide. This loss of carbon and oxygen as carbon monoxide may be a contributing factor in the decrease in the aging effect.

Referring to Fig. 4, it is noticed that the curve for the specimens aged in argon-filled columbium capsules is lower than the curve for specimens aged in quartz. Based on the oxygen effects in the alloys described above, this difference might be attributed to oxygen contamination of the alloy by the argon or by the columbium capsule. No chemical analysis was made on the specimens after testing to confirm this conclusion.

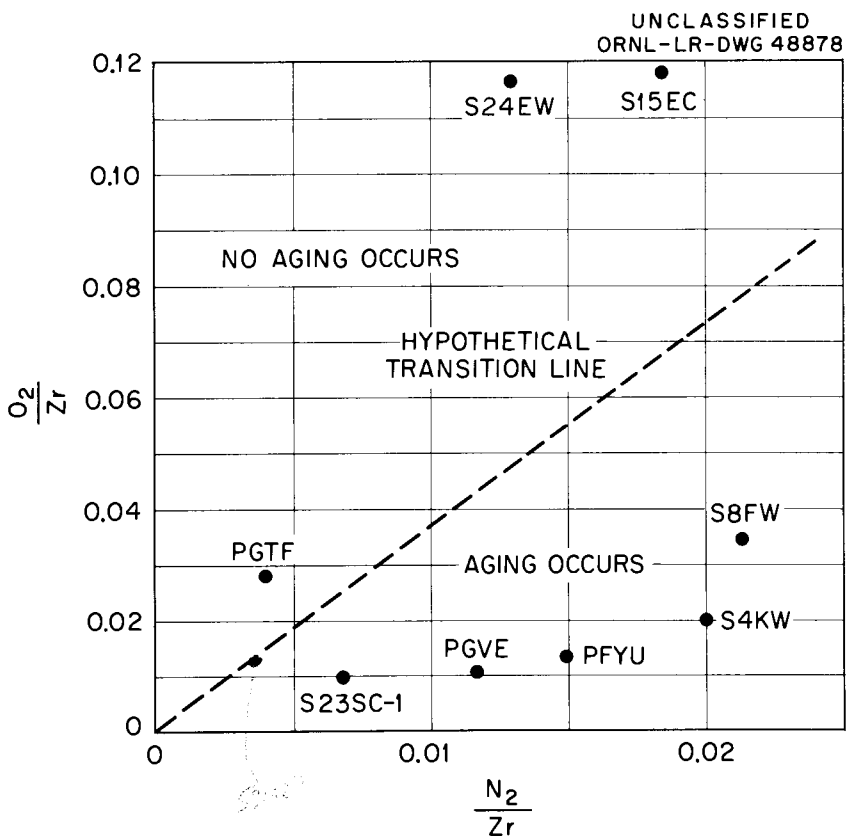

Fig. 11 Plot of O_2/Zr vs N_2/Zr for Eight Columbium-Zirconium Alloys.

Table 4. Effect of Oxygen Contamination on the Aging Reaction in PGVE[a] and S23SC-1[b]

Heat	As Annealed				Aged 100 hr at 927°C				Aging Effect	
	Total O_2 (ppm)[c]	Ultimate Tensile Strength (psi)	Yield Strength (psi)	% Elongation (2 in.)	Total O_2 (ppm)[c]	Ultimate Tensile Strength (psi)	Yield Strength (psi)	% Elongation (2 in.)	Δ Ultimate Tensile Strength	Δ Yield Strength
S23SC-1	120	25 167	12 867	10.5	120	39 980	32 220	4.5	+ 14 823	+ 19 350
S23SC-1	315	23 365	12 875	8.5	347	34 270	30 944	6.0	+ 10 905	+ 18 069
S23SC-1	329	23 055	15 230	6.0	339	32 430	27 795	5.5	+ 9 375	+ 12 565
S23SC-1	403	26 475	14 990	6.5	417	34 165	29 075	4.5	+ 7 690	+ 14 085
S23SC-1	586	26 730	15 120	3.5	595	34 270	22 845	7.0	+ 7 540	+ 7 725
S23SC-1	777	27 865	14 755	8.5	800	29 690	17 695	8.5	+ 1 825	+ 2 940
PGVE	110	24 610	10 445	8	110	33 920	28 440	6	+ 9 310	+ 17 995
PGVE	620	32 315	15 820	12	650	29 846	--	14.5	- 2 475	--

	O_2 (ppm)	N_2 (ppm)	C (ppm)	Zr (Wt %)
[a]As-received chemical analysis	106	115	120	0.98
[b]As-received chemical analysis	120	85	140	1.25

[c]Listed O_2 values are by weight change and represent the O_2 content before heat treatment.

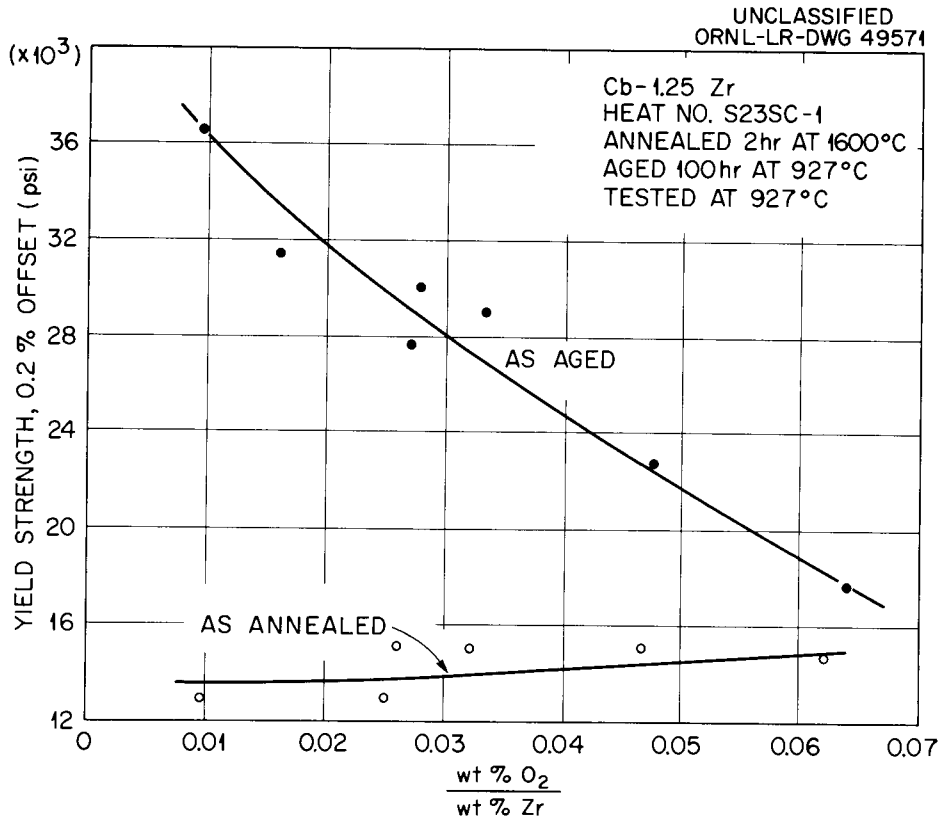

Fig. 12 Effect of Oxygen Contamination on the As-Annealed and As-Aged Yield Strengths of S23SC-1.

CONCLUSIONS

1. The aging phenomena in the Cb–1% Zr alloys were influenced by the annealing temperature. Higher annealing temperatures led to more pronounced aging effects.

2. No correlation was found between observed aging effects and surface contamination from the experimental containers used or from the annealing furnace.

3. The aging or nonaging behavior of the alloys could be correlated with their oxygen/nitrogen ratios and to a lesser extent with their oxygen/carbon ratios.

4. There was a positive correlation between the amount of oxygen added to the alloy and the tendency for aging to occur. When sufficient oxygen was added, the aging tendency could be virtually eliminated.

ACKNOWLEDGMENT

The author wishes to acknowledge the technical assistance of E. E. Hoffman as project coordinator and J. R. DiStefano for their helpful suggestions, especially in regard to the role of oxygen in the alloy.

The author also wishes to thank H. Inouye who, as group leader, made many pertinent and helpful suggestions concerning the experimental work and the preparation of this report.

Thanks are due to the following individuals and groups for their contributions:

J. F. Newsome and J. E. Pope for the preparation and heat treatment of the specimens.

The Analytical Chemistry Division, especially W. R. Laing and Harris Dunn.

The Mechanical Properties Group of the Metallurgy Division, especially C. W. Dollins, *et al.*

The Metallography Group of the Metallurgy Division and particularly W. H. Farmer.

The Metallurgy Reports Office: M. R. Hill, *et al.*

ORNL-2995
Metallurgy and Ceramics
TID-4500 (15th ed.)

INTERNAL DISTRIBUTION

1. G. M. Adamson
2. S. E. Beall
3. R. J. Beaver
4. M. Bender
5. D. S. Billington
6. E. P. Blizard
7. A. L. Boch
8. B. S. Borie
9. C. J. Borkowski
10. W. F. Boudreau
11. G. E. Boyd
12. E. J. Breeding
13. R. B. Briggs
14. J. V. Cathcart
15. C. E. Center (K-25)
16. R. A. Charpie
17. R. E. Clausing
18. R. S. Cockreham
19. T. E. Cole
20. J. H. Coobs
21. J. A. Conlin
22. W. B. Cottrell
23. J. A. Cox
24. F. L. Culler
25. J. E. Cunningham
26. J. H. DeVan
27. J. R. DiStefano
28. D. A. Douglas
29. L. C. Emerson
30. L. B. Emlet (K-25)
31. E. P. Epler
32. J. Foster
33. A. P. Fraas
34. J. H. Frye, Jr.
35. G. A. Garrett (K-25)
36. J. M. Googin (Y-12)
37. R. J. Gray
38. B. L. Greenstreet
39. W. R. Grimes
40. E. Guth
41. J. P. Hammond
42. W. O. Harms
43. R. F. Hibbs (Y-12)
44. T. Hikido
45–54. M. R. Hill
55–59. D. O. Hobson
60. E. E. Hoffman
61. H. W. Hoffman
62. A. Hollaender
63. A. S. Householder
64. H. Inouye
65. P. R. Kasten
66. C. P. Keim
67. M. T. Kelley
68. J. J. Keyes
69. R. B. Korsmeyer
70. P. G. Lafyatis
71. J. A. Lane
72. S. A. Levin (K-25)
73. R. S. Livingston
74. H. G. MacPherson
75. W. D. Manly
76. E. R. Mann
77. R. W. McClung
78. H. E. McCoy
79. H. C. McCurdy
80. W. B. McDonald
81. H. F. McDuffie
82. C. J. McHargue
83. F. R. McQuilkin
84. A. J. Miller
85. E. C. Miller
86. K. Z. Morgan
87. J. P. Murray (Y-12)
88. F. H. Neill
89. M. L. Nelson
90. A. R. Olsen
91. L. G. Overholser
92. P. Patriarca
93. F. S. Patton (Y-12)
94. A. M. Perry
95. D. Phillips
96. M. E. Ramsey
97. P. M. Reyling
98. A. F. Rupp
99. G. Samuels
100. H. W. Savage
101. A. W. Savolainen
102. J. L. Scott
103. O. Sisman
104. E. D. Shipley
105. M. J. Skinner
106. G. M. Slaughter
107. A. H. Snell
108. E. Storto
109. R. D. Stulting
110. C. D. Susano
111. J. A. Swartout

112. A. Taboada
113. E. H. Taylor
114. W. C. Thurber
115. D. B. Trauger
116. E. Von Halle (K-25)
117. C. S. Walker
118. J. L. Wantland
119. A. M. Weinberg
120. J. R. Weir, Jr.
121. J. C. White
122. G. C. Williams
123. C. E. Winters
124. J. Zasler
125. J. H. Koenig (Consultant)
126. R. Smoluchowski (Consultant)
127. C. S. Smith (Consultant)
128. H. A. Wilhelm (Consultant)
129. Health Physics Library
130. Metallurgy Library
131–134. ORNL-Y-12 Technical Library
Document Reference Section
135–169. Laboratory Records Department
170. Laboratory Records RC
171–173. Central Research Library

EXTERNAL DISTRIBUTION

174. J. L. Gregg
Cornell University
175. J. M. Simmons
DRO, AEC, Washington
176. D. K. Stevens
Division of Research, AEC, Washington
177–661. Given distribution as shown in TID-4500 (15th ed.)
under Metallurgy and Ceramics category