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DEVELOPMENT OF HIGH-STRENGTH CORROSION-RESISTANT ZIRCONIUM ALLOYS

by

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Approximately 100 ternary and quaternary sponge-zirconium alloys were screened for structural and cladding applications in a natural-uranium-fueled heavy-water-moderated power reactor. The alloy additions studied included 2 to 4 w/o tin, 0.5 to 2 w/o molybdenum, and 1 to 3 w/o niobium. The effect of 0.1 w/o iron and 0.05 w/o nickel additions to the experimental alloys was evaluated. All compositions were arc melted, rolled at 850 C from a helium-atmosphere furnace, vacuum annealed 4 hr at 700 C, and furnace cooled. Room- and elevated-temperature hardness measurements were used to estimate the tensile strengths of the alloys, while corrosion resistance was evaluated by 1000-hr exposures to static 300 C water.

On the basis of a minimum hardness of 250 DPH and a maximum weight gain of 30 mg per dm^2 *in corrosion testing, seven zirconium alloys appeared promising for intensive evaluation for the intended application: 2 w/o tin-0.5 w/o molybdenum, 2 w/o tin-2 w/o niobium-0.1 w/o iron-0.05 w/o nickel, 2 w/o tin-3 w/o niobium-0.1 w/o iron-0.05 w/o nickel, 3 w/o tin-0.1 w/o iron-0.05 w/o nickel, 3 w/o tin-0.5 w/o molybdenum-0.1 w/o iron- 0.05 w/o nickel, 3 w/o tin-0.5 w/o molybdenum-1 w/o niobium-0.1 w/o iron-0.05 w/o nickel, and 4 w/o tin-0.5 w/o molybdenum.*

INTRODUCTION

In a natural-uranium-fueled heavy-water-moderated reactor, the volume of the reactor core and, therefore, the volume of any parasitic materials are important considerations. If such a reactor is fueled with metallic uranium, the uranium must be clad with a corrosion-resistant material as protection against the corrosive effect of the water. Cladding is also required to maintain retention of the fission products within the fuel element itself. In addition, if such a reactor is designed in such a way that the fuel and the coolant are contained within individual pressure tubes, these tubes must be resistant to corrosion by the coolant and must also have sufficient strength to withstand the pressure required to keep the coolant from boiling.

The material used for these applications must not only meet the requirements of strength and corrosion resistance but must also have a low enough thermal-neutron-capture cross section to provide maximum neutron economy. Zircaloy-2 has excellent corrosion resistance in water at temperatures ranging up to 680 F, but is only a little stronger than pure zirconium. It is possible, however, to use this alloy both as pressure-tube material and as cladding by designing thick enough sections to provide the required strength. Nevertheless, the economy of neutrons in a natural uranium reactor is of such importance that a reduction of the amount of Zircaloy-2 structural material available for parasitic capture of neutrons could provide the margin needed for economic reactor operation. The obvious approach to such a reduction would be to use a material which is substantially stronger than Zircaloy-2 and by so doing reduce the section of the various structural components. Fortunately, it is possible to further improve individual properties of zirconium by alloying. This approach is particularly attractive if the temperature is well below the 680 F associated with the acceptance test for Zircaloy-2 in pressurized-water-reactor applications.

The fact that the coolant-water temperature of the heavy-water-moderated water-cooled natural-uranium-fueled reactor designed and being constructed by the E. I. du Pont de Nemours & Co., Inc., was 570 F was responsible for interest in the development of a zirconium alloy having considerably more strength than Zircaloy-2 and adequate corrosion resistance in 570 F water. Previous investigations had shown that small additions (less than 5 w/o) of molybdenum, niobium, and tin strengthen zirconium without markedly decreasing its corrosion resistance(1) and that the possibilities for developing a "tailor-made" zirconium alloy for the specific application were good. In an attempt to choose several potential alloys a research program was performed for the purpose of surveying a number of alloys for future evaluation. This investigation and the results observed are discussed in detail in subsequent sections of this report.

PREPARATION OF ALLOYS

Nine series of alloys were prepared: ternary zirconium-base alloys containing 2.0, 3.0, and 4.0 w/o tin plus 0 to 2.0 w/o molybdenum, ternaries containing 2.0, 3.0, and 4.0 w/o tin plus 0 to 3.0 w/o niobium, and quaternary alloys containing 2.0, 3.0, and 4.0 w/o tin plus 0.5 to 2.0 w/o molybdenum and 1.0 to 3.0 w/o niobium. Duplicate melts of each alloying composition were prepared. These duplicate melts differed in iron and nickel content. In one melt, 0.1 w/o iron and 0.05 w/o nickel were added while in the corresponding alloy no iron or nickel was added.

Alloys were prepared by arc melting (tungsten electrode) sponge-base zirconium and appropriate alloying additions six times. The 50-g buttons were then cast into 1 by 3/4 by 1/4-in. bars prior to fabrication. Table 1 shows analyses of melting stock used. In order to ascertain if the nominal compositions of the alloys prepared were within experimental error, spot chemical analyses were performed. Table 2 lists the results of representative analyses.

Alloys containing 2.0 and 3.0 w/o tin were hot rolled at 850 C from a helium atmosphere to 0.070 in. Reductions of 15 per cent per pass were obtained with no edge cracking. Alloys containing 4.0 w/o tin showed slight edge cracking, and the amount of reduction was therefore reduced to 10 per cent per pass. No further cracking was observed. All alloys were annealed in evacuated Vycor tubes at 700 C for 4 hr and furnace cooled. After annealing, specimens for corrosion evaluation, hardness measurements, and metallography were sheared from the annealed sheet.

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(1) References at end.

TABLE 1. VENDOR'S ANALYSES OF MELTING STOCKS

Impurity	Analyses of Indicated Base Stock, ppm			
	Zirconium Sponge	Tin	Molybdenum	Niobium
Aluminum	43	--	--	50
Arsenic	--	30.3	--	--
Boron	<0.2	--	--	--
Carbon	--	--	2	40
Chlorine	1400	--	--	--
Chromium	50	--	--	<100
Cobalt	<5	--	--	--
Copper	20	3.0	--	<100
Hafnium	62	--	--	400
Hydrogen	27	--	--	4.7
Iron	150	50	--	<100
Lead	5	20	--	--
Magnesium	938	--	--	--
Manganese	15	--	--	--
Molybdenum	--	--	Balance	50
Nickel	<10	--	--	--
Niobium	--	--	--	Balance
Nitrogen	34	--	2	29
Oxygen	1000	--	--	870
Silicon	50	--	--	<100
Tantalum	--	--	--	<1500
Tin	--	Balance	--	--
Titanium	<30	--	--	50
Vanadium	<20	--	--	--
Zirconium	Balance	3	--	500

TABLE 2. ANALYSES OF SPONGE ZIRCONIUM-BASE ALLOYS

Nominal Composition, w/o	Analyzed Composition, w/o				
	Sn	Mo	Nb	Fe	Ni
Zr-2.0 Sn-0.5 Mo	2.1	0.43	--	--	--
Zr-3.0 Sn-0.5 Mo-1.0 Nb-0.1 Fe 0.05 Ni	3.1	0.37	1.3	0.099	0.057
Zr-4.0 Sn-2.0 Mo-3.0 Nb	4.0	1.4	3.7	--	--

ALLOY HARDNESS AT ROOM AND ELEVATED TEMPERATURES

Room-temperature hardness values were used as a tool to estimate the tensile strengths of alloys being studied. The tensile strength was estimated from the hardness-strength relationship.(2) A room-temperature hardness parameter of 250 was selected since it would yield an estimated increase of 12,000 psi in the room-temperature tensile strength over that of Zircaloy-2.

Room-temperature hardness values of alloys studied showed progressive increases in hardness for total alloying additions up to 5 w/o. Above 5 w/o no appreciable increases in hardness were noted up to 9 w/o total alloying content. Figure 1 shows graphically this increase in hardness. The greatest increases in hardnesses appear to be due to the tin additions. Compositional variations from the nominal values make it difficult to assign any significance to hardness increases or decreases of individual alloys. Room-temperature hardness numbers are shown in Table 3.

After evaluation of the room-temperature hardness values, alloys were selected which showed promise of high strength (based on hardness-strength relationship) for hot-hardness study. The hardness of a large number of alloys had been increased significantly; therefore, corrosion data were also taken into consideration in selecting alloys for hot-hardness measurements. Diamond-pyramid hardnesses of the alloys selected were obtained at elevated temperatures by means of a vacuum hot-hardness machine. In this apparatus, the specimen and stage are heated by a resistance-type furnace immediately surrounding them, and the specimen is placed directly over thermocouples fitted into the stage from below. Indentations were made by lowering the indenter until its full weight (730 g) rested on the specimen for 15 sec. At least five indentations were made at 200, 300, and 400 C. Four impressions were made at 600, 700, 800, and 900 C.

Increasing the tin content resulted in increased hot-hardness values. The effect is shown in Figure 2. The values obtained here for the 2.0 and 4.0 w/o tin alloys show good agreement with previously reported data.(2) Increasing the tin content from 1.5 to 4.0 w/o results in an increase in hardness at 300 C of 50 DPH. This corresponds to an estimated(3) increase in tensile strength of 15,000 psi. Increasing the tin content in alloys containing 0.5 w/o molybdenum also results in significant increases in hardness numbers at 300 C (above the hardness of Zircaloy-2). The hardness is not increased at 300 C with increases in tin content from 3.0 to 4.0 w/o tin. This is shown in Figure 3. In alloys containing 1.0 w/o molybdenum and 1 w/o niobium, there is an increase in hardness over that of Zircaloy-2 of 90 DPH (105 to 195 DPH) at 300 C for alloys containing 4 w/o tin. This is shown graphically in Figure 4. It appears that in alloys containing larger amounts of total alloying additions, increases in tin content result in greater increases in hot hardness than in the more dilute alloys (Figures 3 and 4). Figure 5 shows the curves obtained for alloys containing 2.0 w/o molybdenum and 3.0 w/o niobium. The greater increases in hardness evident in Figure 5 are due to total alloying content. In Figure 6, where the total alloying content (excluding tin) is shown, it appears that other alloying additions and tin have an equal effect on the hot-hardness values at 300 C. Table 4 lists the hot-hardness values obtained on selected representative alloys.

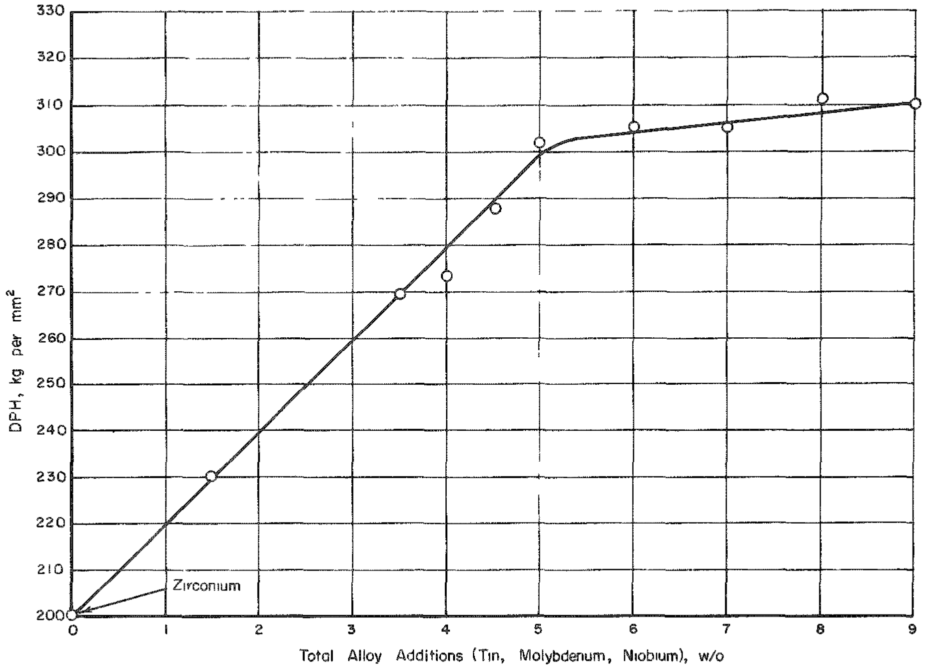

FIGURE 1. EFFECT OF TOTAL ALLOYING ADDITIONS ON ROOM-TEMPERATURE HARDNESS OF ZIRCONIUM-BASE STOCK

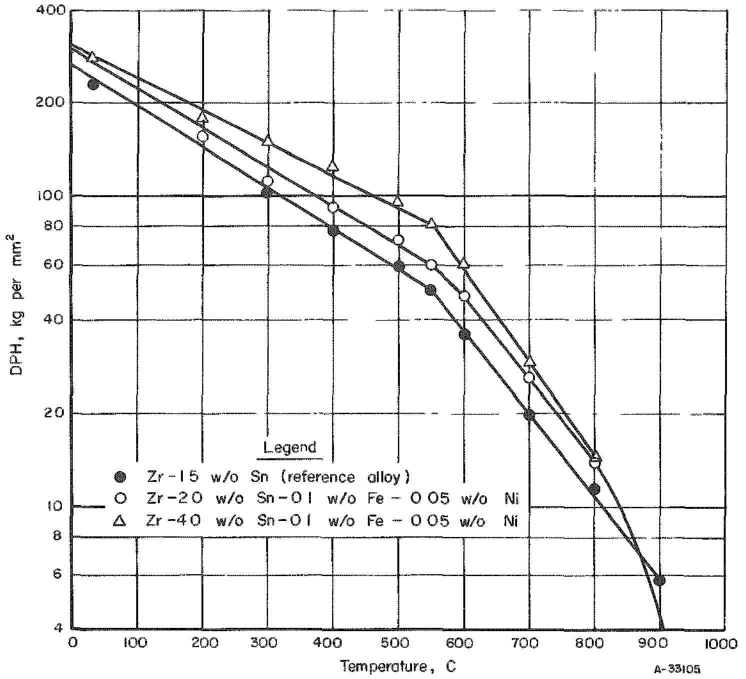

FIGURE 2. EFFECT OF INCREASING TIN CONTENT ON THE HOT HARDNESS OF ZIRCONIUM-BASE ALLOYS

TABLE 3. ROOM-TEMPERATURE HARDNESSES AND CORROSION BEHAVIOR IN 300 C WATER OF THE ZIRCONIUM ALLOYS PREPARED IN THE PROGRAM

	Nominal Alloying Additions (Balance Zirconium), w/o						1000-Hr Corrosion in 300 C Water	
Alloy	Sn	Mo	Nb	Fe	Ni	Room-Temperature Hardness, DPH	Weight Gain[(a)], mg per dm^2	Appearance[(b)]
1	2.0	--	--	--	--	262	12	G
2	2.0	--	--	0.1	0.05	279	23	G
3	2.0	0.5	--	--	--	299	18	G
4	2.0	0.5	--	0.1	0.05	256	23	G
5	2.0	1.0	--	--	--	292	25	G
6	2.0	1.0	--	0.1	0.05	274	25	M
7	2.0	2.0	--	--	--	323	30	M
8	2.0	2.0	--	0.1	0.05	285	27	M
9	2.0	--	1.0	--	--	285	25	M
10	2.0	--	1.0	0.1	0.05	264	26	M
11	2.0	--	2.0	--	--	295	12	G
12	2.0	--	2.0	0.1	0.05	307	14	G
13	2.0	--	3.0	--	--	361	29	M
14	2.0	--	3.0	0.1	0.05	297	14	M
15	2.0	0.5	1.0	--	--	279	25	M
16	2.0	0.5	1.0	0.1	0.05	260	23	M
17	2.0	0.5	2.0	--	--	258	27	M
18	2.0	0.5	2.0	0.1	0.05	270	21	M
19	2.0	0.5	3.0	--	--	274	19	M
20	2.0	0.5	3.0	0.1	0.05	240	18	S
21	2.0	1.0	1.0	--	--	283	33	S
22	2.0	1.0	1.0	0.1	0.05	264	28	S
23	2.0	1.0	2.0	--	--	283	34	W
24	2.0	1.0	2.0	0.1	0.05	283	26	S
25	2.0	1.0	3.0	--	--	276	24	S
26	2.0	1.0	3.0	0.1	0.05	290	44	W
27	2.0	2.0	1.0	--	--	294	58	W
28	2.0	2.0	1.0	0.1	0.05	312	68	W
29	2.0	2.0	2.0	--	--	302	50	W
30	2.0	2.0	2.0	0.1	0.05	308	62	W
31	2.0	2.0	3.0	--	--	302	68	W
32	2.0	2.0	3.0	0.1	0.05	307	62	W
33	3.0	--	--	--	--	279	3	G
34	3.0	--	--	0.1	0.05	312	12	G
35	3.0	0.5	--	--	--	283	12	G
36	3.0	0.5	--	0.1	0.05	304	15	G
37	3.0	1.0	--	--	--	276	19	G
38	3.0	1.0	--	0.1	0.05	281	25	G
39	3.0	2.0	--	--	--	279	27	M
40	3.0	2.0	--	0.1	0.05	274	24	G
41	3.0	--	1.0	--	--	270	17	G
42	3.0	--	1.0	0.1	0.05	253	22	G
43	3.0	--	2.0	--	--	292	15	G
44	3.0	--	2.0	0.1	0.05	292	27	M
45	3.0	--	3.0	--	--	297	25	M
46	3.0	--	3.0	0.1	0.05	299	23	M
47	3.0	0.5	1.0	--	--	306	19	G
48	3.0	0.5	1.0	0.1	0.05	319	19	G
49	3.0	0.5	2.0	--	--	297	20	G
50	3.0	0.5	2.0	0.1	0.05	281	25	M
51	3.0	0.5	3.0	--	--	289	24	M

TABLE 3. (Continued)

	Nominal Alloying Additions (Balance Zirconium), w/o						1000-Hr Corrosion in 300 C Water	
Alloy	Sn	Mo	Nb	Fe	Ni	Room-Temperature Hardness, DPH	Weight Gain(a), mg per dm^2	Appearance(b)
52	3.0	0.5	3.0	0.1	0.05	285	29	S
53	3.0	1.0	1.0	--	--	327	23	M
54	3.0	1.0	1.0	0.1	0.05	312	33	S
55	3.0	1.0	2.0	--	--	309	34	S
56	3.0	1.0	2.0	0.1	0.05	299	47	W
57	3.0	1.0	3.0	--	--	293	32	W
58	3.0	1.0	3.0	0.1	0.05	294	34	S
59	3.0	2.0	1.0	--	--	312	47	W
60	3.0	2.0	1.0	0.1	0.05	317	40	W
61	3.0	2.0	2.0	--	--	299	42	W
62	3.0	2.0	2.0	0.1	0.05	319	61	W
63	3.0	2.0	3.0	--	--	322	46	W
64	3.0	2.0	3.0	0.1	0.05	319	68	W
65	4.0	--	--	--	--	309	21	G
66	4.0	--	--	0.1	0.05	304	21	G
67	4.0	0.5	--	--	--	333	21	G
68	4.0	0.5	--	0.1	0.05	322	24	G
69	4.0	1.0	--	--	--	293	19	G
70	4.0	1.0	--	0.1	0.05	299	24	G
71	4.0	2.0	--	--	--	294	17	G
72	4.0	2.0	--	0.1	0.05	304	26	M
73	4.0	--	1.0	--	--	330	19	G
74	4.0	--	1.0	0.1	0.05	287	21	G
75	4.0	--	2.0	--	--	299	16	G
76	4.0	--	2.0	0.1	0.05	302	19	G
77	4.0	--	3.0	--	--	302	20	M
78	4.0	--	3.0	0.1	0.05	299	26	M
79	4.0	0.5	1.0	--	--	322	20	G
80	4.0	0.5	1.0	0.1	0.05	333	16	G
81	4.0	0.5	2.0	--	--	322	14	G
82	4.0	0.5	2.0	0.1	0.05	306	22	M
83	4.0	0.5	3.0	--	--	333	20	M
84	4.0	0.5	3.0	0.1	0.05	314	22	S
85	4.0	1.0	1.0	--	--	330	20	G
86	4.0	1.0	1.0	0.1	0.05	306	28	S
87	4.0	1.0	2.0	--	--	317	27	S
88	4.0	1.0	2.0	0.1	0.05	304	26	S
89	4.0	1.0	3.0	--	--	322	26	S
90	4.0	1.0	3.0	0.1	0.05	289	26	S
91	4.0	2.0	1.0	--	--	308	31	S
92	4.0	2.0	1.0	0.1	0.05	302	24	S
93	4.0	2.0	2.0	--	--	311	26	W
94	4.0	2.0	2.0	0.1	0.05	302	35	W
95	4.0	2.0	3.0	--	--	318	29	W
96	4.0	2.0	3.0	0.1	0.05	301	52	W
97	1.5	--	--	--	--	243	26	G
98	1.5	--	--	0.1	0.05	232	25	G

(a) Average of three specimens.

(b) Code:

G = Black oxide
M = Milky
S = Slightly mottled
W = Mottled.

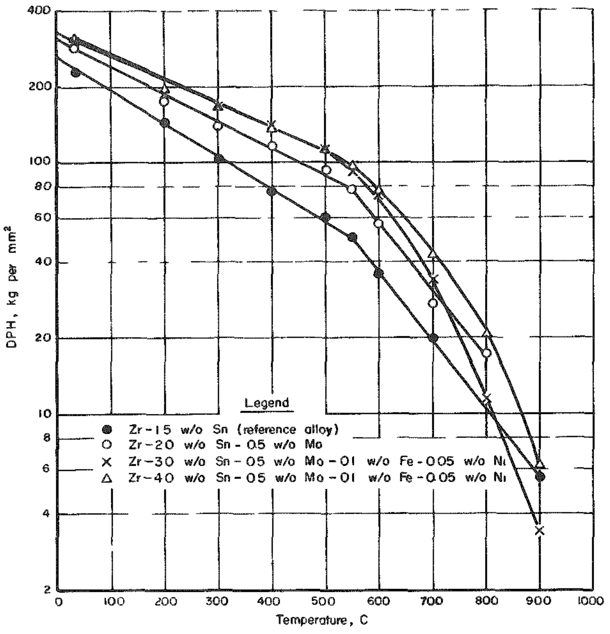

FIGURE 3. EFFECT OF INCREASING TIN CONTENT ON HOT HARDNESS IN TERNARY ZIRCONIUM ALLOYS CONTAINING 0.5 w/o MOLYBDENUM

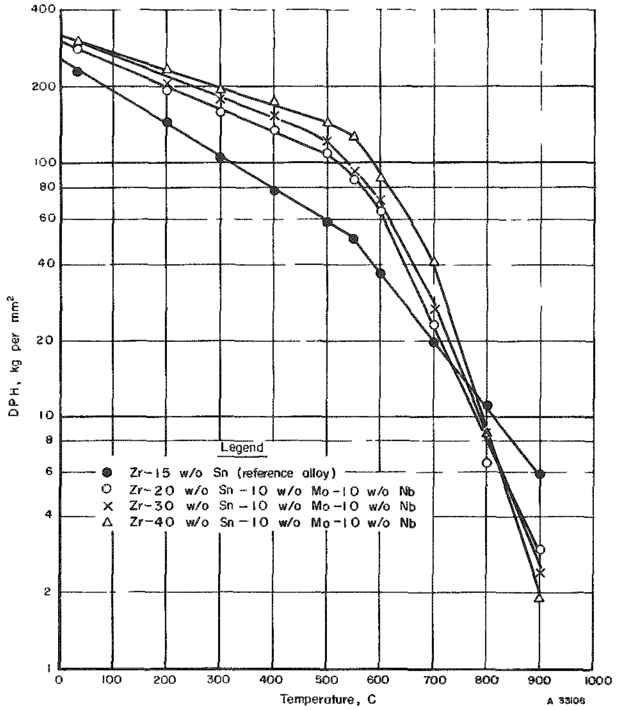

FIGURE 4. EFFECT OF INCREASING TIN CONTENT ON HOT HARDNESS IN QUATERNARY ZIRCONIUM ALLOYS CONTAINING 1.0 w/o MOLYBDENUM AND 1.0 w/o NIOBIUM

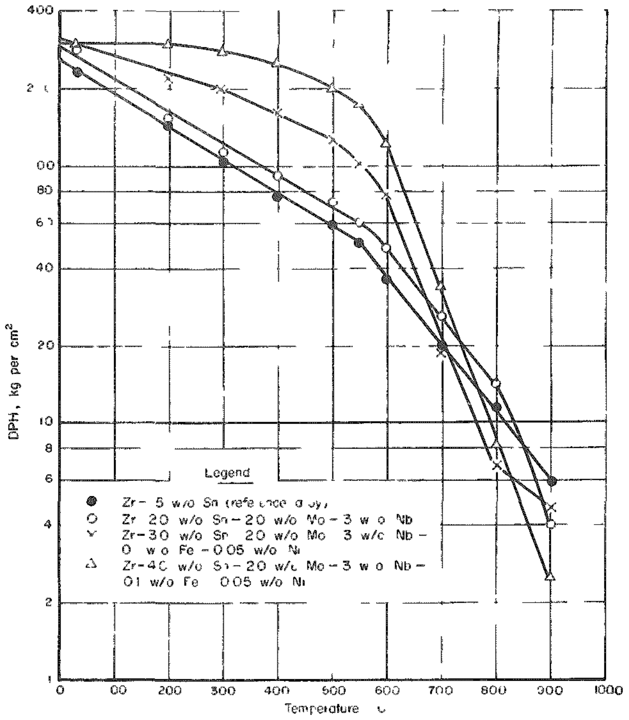

FIGURE 5. EFFECT OF INCREASING TIN CONTENT ON HOT HARDNESS IN QUATERNARY ZIRCONIUM ALLOYS CONTAINING 2.0 w/o MOLYBDENUM AND 3. w/o NIOBIUM

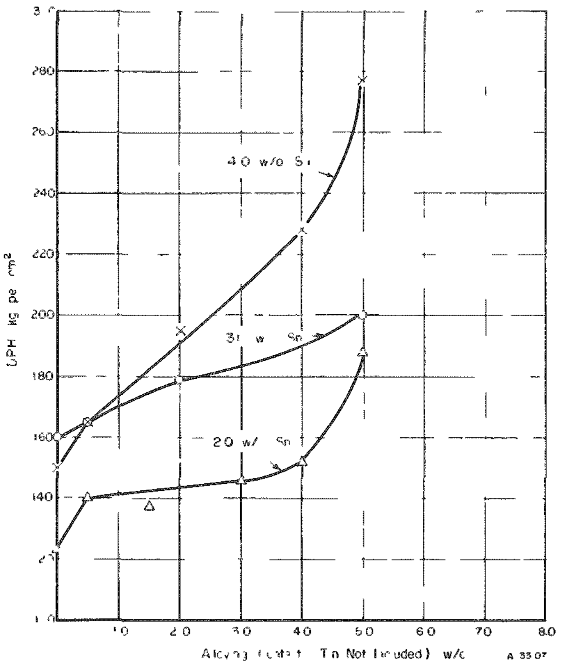

FIGURE 6. EFFECT ON ALLOYING ADDITIONS ON HOT HARDNESS OF ZIRCONIUM AT 300 C

TABLE 4. HARDNESS OF SPONGE-ZIRCONIUM ALLOYS AT ELEVATED TEMPERATURES

Nominal Alloying Additions (Balance Zirconium), w/o					DPHN at Temperature Shown, kg per mm^2									
Sn	Mo	Nb	Fe	Ni	Room	200 C	300 C	400 C	500 C	550 C	600 C	700 C	800 C	900 C
2.0	--	--	0.1	0.05	292	157	113	92.7	73.2	60.9	48.2	26.2	14.2	4.0
2.0	0.5	--	--	--	289	174	140	117	93.2	79.1	57.5	27.3	17.4	--
2.0	0.5	1.0	--	--	264	168	137	120	95.8	76.4	54.2	24.6	8.3	--
2.0	1.0	1.0	--	--	287	199	160	136	110	86.1	65.7	23.7	6.6	3.0
2.0	1.0	2.0	--	--	267	168	146	124	103	85.2	58.8	20.7	6.2	--
2.0	1.0	3.0	--	--	274	177	145	126	108	97.2	69.6	27.4	9.3	--
2.0	2.0	3.0	--	--	312	209	187	167	131	106	76.2	20.9	8.0	6.0
3.0	0.5	--	0.1	0.05	299	188	165	142	112	92.7	72.6	34.8	11.4	3.4
3.0	--	3.0	--	--	263	182	159	138	111	91.4	64.6	24.1	8.1	1.9
3.0	1.0	1.0	--	--	292	203	179	154	121	91.7	70.9	26.9	8.6	2.4
3.0	2.0	3.0	0.1	0.05	295	225	200	165	127	104	77.4	19.6	5.9	4.6
4.0	--	--	0.1	0.05	287	177	150	127	98.6	81.3	61.4	29.3	14.7	--
4.0	0.5	--	0.1	0.05	304	196	165	135	111	96.0	77.1	42.9	20.6	6.2
4.0	--	3.0	--	--	270	193	163	137	118	105	72.7	27.8	10.9	2.1
4.0	1.0	1.0	--	--	299	233	195	178	148	128	88.9	40.3	8.8	1.9
4.0	1.0	3.0	0.1	0.5	279	261	228	212	165	120	77.0	25.6	7.9	2.7
4.0	2.0	3.0	0.1	0.5	299	299	277	249	200	177	122	34.4	8.3	2.5
Zircaloy-2(a)					232	145	104	77.6	59.3	50.1	36.6	19.9	11.4	5.8

(a) Reference alloy made up with same sponge zirconium as alloys listed above.

Using the hardness of Zircaloy-2 at both room temperature (220 DPH) and at 300 C (104 DPH) as a reference, it can be seen that large increases in hardness have been obtained. At both room and elevated temperatures the most beneficial addition appears to be tin and tin in combination with molybdenum.

ALLOY CORROSION EVALUATION

A maximum total weight-gain corrosion parameter of 30 mg per dm^2 in 1000 hr was selected as a basis for screening candidate alloys. It should be pointed out that, to establish an expected service life in pressurized-water reactors, substantially longer reference periods would be necessary. Specimens for corrosion studies at 300 C in high-purity water were prepared in triplicate by shearing test coupons 1 by 0.75 by 0.70 in. from the wrought sheet. Approximately 0.003 in. was machined from each surface, and an additional 0.002 in. was pickled from the surfaces in a HNO_3-5 volume per cent HF-50 volume per cent H_2O solution. The specimens were exposed to static demineralized water at 300 C for a total of 1000 hr, and removed from test, weighed, and examined at intermediate time intervals of 168, 336, 672, and 1000 hr. Total weight gains in milligrams per square decimeter of surface were calculated for each period. Results for 1000 hr of exposure are summarized in Table 3.

The effect of niobium additions on the corrosion behavior of the zirconium alloys is illustrated in Figure 7. No consistent trends are evident from these results. In general, niobium appears to have little effect on the weight gains obtained after 1000 hr of exposure to 300 C water. This is consistent with reported observations that binary niobium additions have little influence on the corrosion behavior of zirconium.(3) There are indications from the data in Figure 7 that increasing niobium increases the amount of corrosion in 2 w/o molybdenum-0.1 w/o iron-0.05 w/o nickel-3 to 4 w/o tin alloys. The reason for this effect is not yet apparent.

Figure 8 shows the effect of molybdenum additions on the weight gains of the zirconium alloys after 1000 hr of exposure to 300 C water. It is obvious from these curves that increasing the molybdenum content results in increased attack in the alloys. (This is in line with the known harmful effects of molybdenum additions to zirconium.(3)) The adverse effects of molybdenum are most evident at the higher niobium levels and indicate the possibility of a cumulative effect of the alloy additions.

The weight gains obtained after exposing binary zirconium-tin alloys 1000 hr to 300 C water are compared in Figure 9. There appears to be no effect of tin on corrosion behavior under these conditions. However, exposure at higher temperatures and for longer periods would be expected to reveal a drop in corrosion resistance with increasing tin content. An interesting, and as yet unexplained, beneficial effect of tin was observed when total alloy content was considered. This effect is shown in Figure 10. At the 4 w/o tin level, all specimens containing up to 5 w/o total alloy additions exhibited weight gains of less than 30 mg per dm^2 in 1000 hr of exposure. A progressive increase in attack was noted at the lower tin levels of 3 and 2 w/o. Although tin is known to counteract the adverse effects of nitrogen, and, to a lesser extent, those of aluminum, carbon, and titanium, at impurity levels, it is not considered as exerting significant beneficial effects in the case of molybdenum, niobium, and other elements at alloying levels.

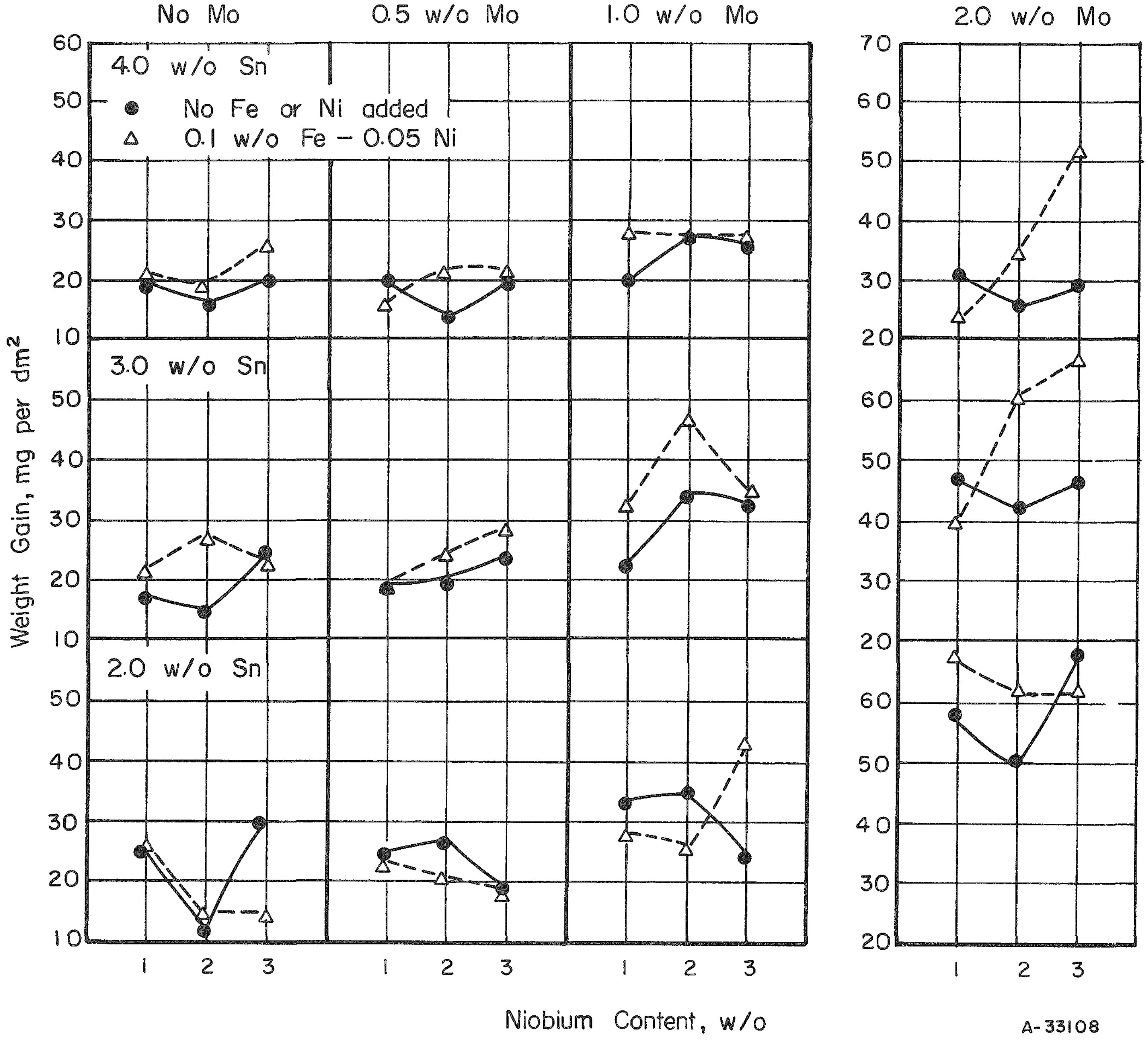

FIGURE 7. EFFECT OF NIOBIUM ADDITIONS ON THE CORROSION BEHAVIOR OF ZIRCONIUM-MOLYBDENUM ALLOYS

Specimens were exposed 1000 hr to 300 C water.

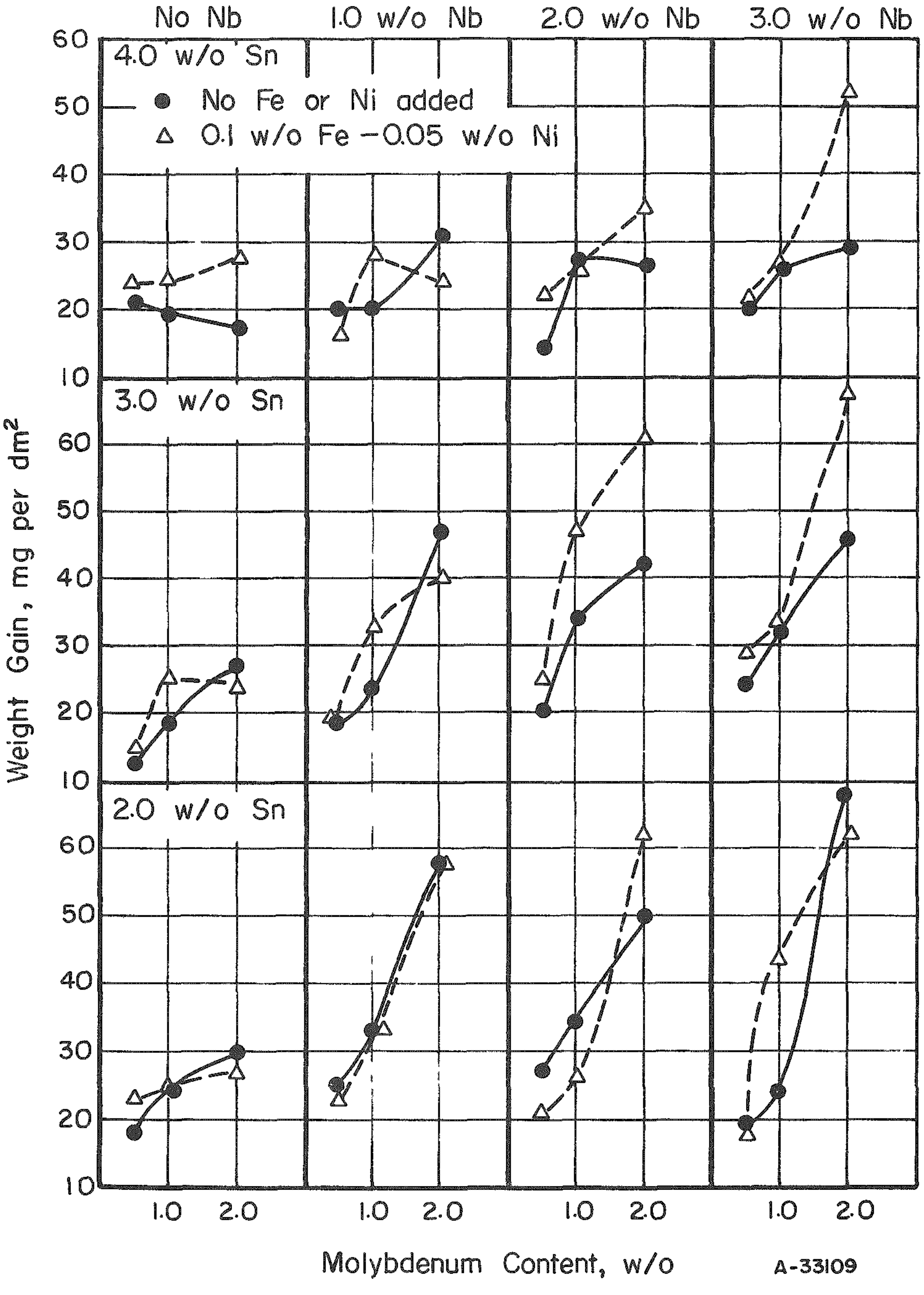

FIGURE 8. EFFECT OF MOLYBDENUM ADDITIONS ON THE CORROSION BEHAVIOR OF ZIRCONIUM-NIOBIUM ALLOYS

Specimens were exposed 1000 hr to 300 C water.

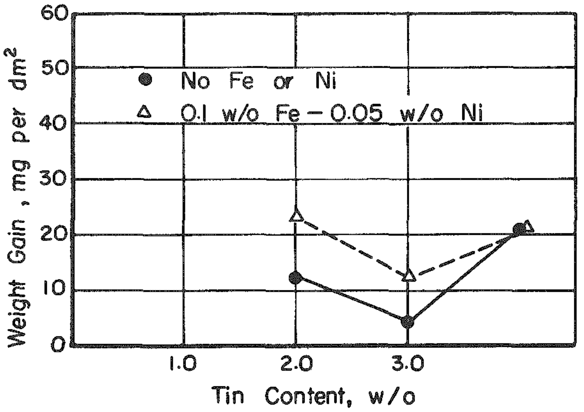

FIGURE 9. COMPARISON OF WEIGHT GAINS OF ZIRCONIUM-TIN ALLOYS EXPOSED 1000 HR TO 300 C WATER

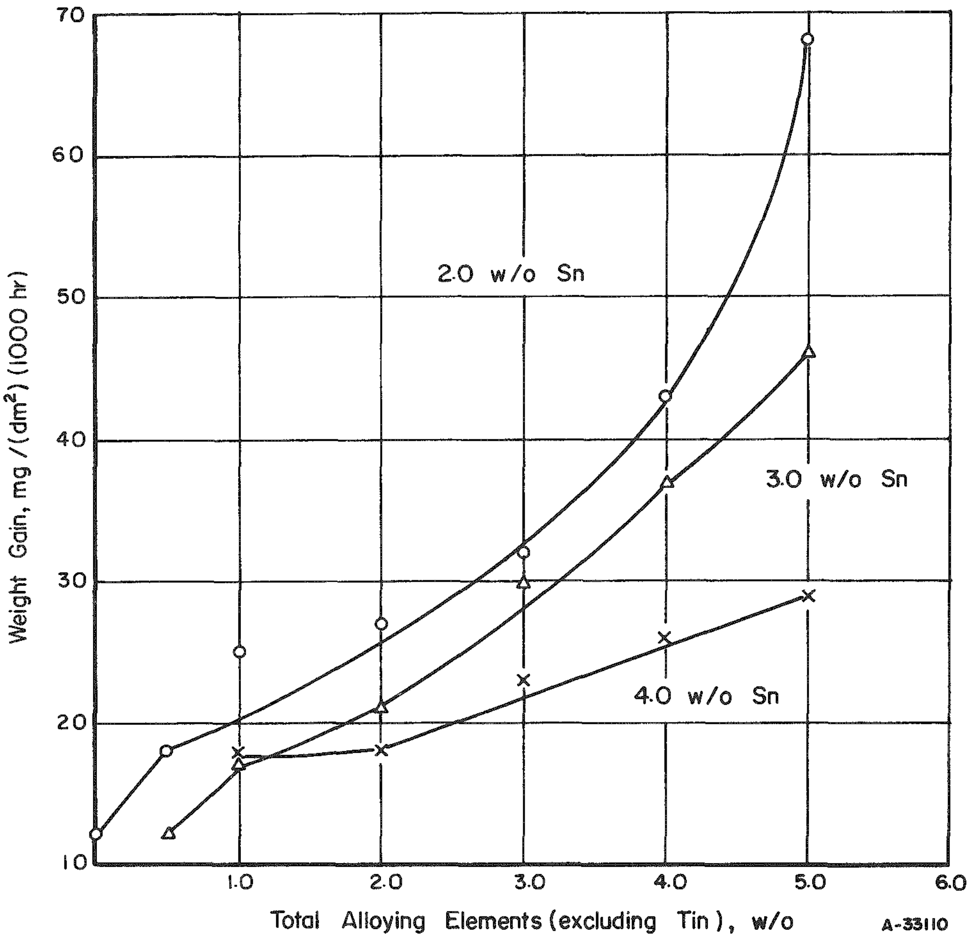

FIGURE 10. EFFECT OF TIN ON TOTAL WEIGHT GAIN OF ZIRCONIUM-BASE ALLOYS EXPOSED 1000 HR TO 300 C WATER

TABLE 5. ALLOYS SUGGESTED FOR FURTHER EVALUATION

Nominal Alloying Additions (Balance Zirconium), w/o					DPH, kg per mm^2		Weight Gain in 300 C Water, mg/(dm^2)(1000 hr)	Approximate Calculated Thermal-Neutron Cross Section, barn per atom
Sn	Mo	Nb	Fe	Ni	Room Temperature	300 C		
2.0	0.5	--	--	--	290	140	18	0.198
2.0	--	2.0	0.1	0.05	307	140(a)	14	0.200
2.0	--	3.0	0.1	0.05	297	150(a)	14	0.213
3.0	--	--	0.1	0.05	312	160	12	0.189
3.0	0.5	--	0.1	0.05	304	165	15	0.199
3.0	0.5	1.0	0.1	0.05	319	160(a)	19	0.209
4.0	0.5	--	--	--	333	165	21	0.205
Zircaloy-2(b)		--	--	--	230	104	24	0.195
Zircaloy-2(c)		--	--	--	210	104	13	0.195

(a) Estimated hot-hardness values from similar alloys.

(b) Values obtained in this testing program.

(c) Values obtained from literature.

CONCLUSIONS

Two general conclusions can be drawn from the results of the program:

(1) Alloys can be prepared which show increased hardnesses over Zircaloy-2 at both room and elevated temperatures while still retaining corrosion resistance in 300 C water for 1000 hr which is comparable to that of Zircaloy-2.

(2) The survey has shown that seven alloys have short-time corrosion properties in 300 C water comparable to Zircaloy-2 and strengths greater than Zircaloy-2.

RECOMMENDATIONS

Completion of this phase of the program has indicated that several alloys can be selected which show promise as a prospective cladding material for use in water at 300 C. Alloys which show the optimum combination of hardness at room temperature and 300 C, corrosion life in 300 C water, and thermal-neutron cross section (calculated(4)) are shown in Table 5.

Naturally, further evaluation of these alloys is necessary before they can be of use as cladding material. It will be necessary to determine their mechanical and creep properties and their thermal conductivity. Alloys which show the best combinations of these properties should undergo further evaluation in a well-planned irradiation program.

ACKNOWLEDGMENT

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