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UNITED STATES ATOMIC ENERGY COMMISSION

OXIDATION RESISTANCE OF NIOBIUM-BASE ALLOYS

By
H. J. Cleary

JULY 13, 1956
~~May 31, 1957~~

Nuclear Metals, Inc.
Cambridge, Massachusetts

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Oxidation Resistance

of

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Cambridge, Massachusetts

Contract AT(30-1)-1565

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I. SUMMARY

A program has been under way for the development of a niobium-base alloy with oxidation-resistant properties above 2000°F (1093°C); a 1000-fold improvement over the oxidation resistance of unalloyed niobium at these temperatures was desired. A considerable number of binary and ternary niobium-base alloys have been investigated for oxidation resistance at 980°C.

The following alloying elements were found to be somewhat beneficial when added in sufficient amounts to niobium: Al, Cr, Ti, Sn, and Co. Addition of other binary elements lowered the oxidation resistance of niobium: V, Cu, Mg, U, Zn, and Si. Elements which had little effect on the oxidation rate of the base metal were Be, Ni, Fe, and Mn. Ternary alloys with better oxidation resistance than unalloyed niobium were:

Nb-20 w/o Cr-6 w/o Al

Nb-10 w/o Cr-2 w/o Al

Nb-20 a/o Ti-5 a/o Be

Nb-25 a/o Ti-10 a/o Al

A ternary alloy with low resistance was Nb-25 a/o Cr-5 a/o Be.

The best of these binary and ternary alloys (Nb-25 a/o Ti, Nb-20 a/o Ti-5 a/o Be, Nb-25 a/o Ti-10 a/o Al) showed less than a 40-fold improvement in the oxidation rate of unalloyed niobium at 980°C (1800°F).

A similar study has been in progress at BMI. Where the two studies overlap, the BMI and NMI results are in fairly good agreement. (A discrepancy appears in the results obtained for the Nb-10 w/o V alloy, for which BMI reports a low oxidation rate and NMI a high rate.) The best BMI alloys

(Nb-25 a/o Ti, Nb-20 a/o Cr-5 a/o Mo) exhibit less than a 30-fold improvement in the unalloyed niobium oxidation rate at 1000°C (1832°F).

The work at NMI has included the preparation and testing of a quaternary niobium-base alloy containing 23 w/o Cr-10 w/o Al-15 w/o Si (23.2 a/o Cr-19.4 a/o Al-28.0 a/o Si). The oxidation-resistant properties of this alloy were found to be far superior to those of all the binary and ternary alloys tested up to the present time; the rate obtained at approximately 1000°C was more than 1000 times smaller than that for the base metal. Increasing the temperature to 1200°C (2200°F) resulted in a 10-fold increase in the oxidation rate of this alloy. Also included in the run at 1200°C were specimens of Fe-25 w/o Cr-5 w/o Al alloy, which showed roughly 4 times better oxidation resistance than the Nb-23 w/o Cr-10 w/o Al-15 w/o Si alloy.

The results established for the relative effectiveness of the various binary elements in lowering the oxidation rate of the base metal do not agree well with the limited theoretical principles available at the present time.

II. THEORETICAL CONSIDERATIONS

The problem of improving the oxidation properties of base metals often has been solved by the addition of alloying elements which lead to the formation of a protective surface layer. A theory of oxidation that would allow complete prediction of the effectiveness of alloying additions has not yet been formulated. Some general principles have emerged, however. The resistance of alloys to surface attack at elevated temperatures depends largely on the type of scale formed. A desirable scale would: (1) be tough and adherent, (2) be of proper density relative to the base metal (to prevent either porosity due to low oxide/metal volume or cracking due to build-up of excess compressive stresses in the scale for high oxide/metal volume), (3) contain no volatile or low-melting constituents, (4) be of stable composition, and (5) have small permeability for either metal or oxygen.

According to a number of investigators, a low oxidation rate of an alloy is related to the formation of an oxide scale possessing low electrical conductivity (indicating low metal diffusion), high melting point, and very few defects (so that migration processes are slow).[1,2,3,4] This has been achieved by the addition of alloying elements which form refractory oxides to metals and alloys with inadequate oxidation resistance of their own. Such an alloying element must have a high affinity for oxygen if the oxide of this element is to form preferentially, and there must be enough of it to form a complete oxide layer.

The added element may occur in the scale in several forms, depending, for the most part, upon its relative oxidizability with respect to the base metal. Aluminum, silicon, and chromium, when added in small amounts to iron, may occur in the inner FeO layer of scale adjacent to the steel base either as their own oxides or as double oxides with FeO. The concentration of such elements in the inner layer of scale may be as high as 4 times their concentration in the alloy. In the two outer layers of scale (Fe_3O_4, Fe_2O_3), the added element may decrease to 10 percent of its concentration in the base metal. When a larger amount of one of these elements is added, the concentration in the inner scale rises continuously during oxidation until the inner scale consists almost entirely of the refractory oxide, with a correspondingly low diffusion rate of cations or anions through the refractory oxide. The lowest oxidation rate is to be expected when the scale adjacent to the metal consists entirely of such a refractory oxide.[5] For example, by using a slightly oxidizing atmosphere while preheating copper that contained an amount of aluminum insufficient to retard oxidation appreciably in air, Price and Thomas[6] were able to form a layer of refractory aluminum oxide on the copper which effectively stopped further scaling when the metal was reheated in air. Hence, for the formation of a new, protective layer of oxide, the alloying element should have a greater affinity for oxygen than does the base metal.

If the activity of the alloying element to oxygen is less than that of the base metal, its oxide may appear in segregated areas and therefore give no protection. Also, when alloys containing additives of the noble metals are oxidized, metallic particles of these elements may be found in the scale.

Table I lists a number of refractory oxides arranged in order of decreasing electrical resistivity at elevated temperatures. Table II includes oxides arranged in order of increasing free energies of formation (decreasing thermodynamic stability). Based on these two considerations alone, electrical resistivity and thermodynamic stability of the oxides, the metallic elements near the top of each list would be selected as alloying elements to improve the oxidation resistance of a metal.

There are other considerations in selecting an alloying element. An obvious requirement is that an added element should be soluble in the base metal if it is to provide general surface protection.

If an intermediate oxide layer is to provide protection against oxidation one of the conditions which must be fulfilled is that the diffusion rates of cations and anions within the layer must be small.[7] Since smaller ions diffuse faster, the oxidation rate is thought to be controlled by the diffusion of metal cations which are much smaller in diameter than the oxygen anions. It might be expected that the entry and passage of base metal cations through a refractory oxide film would be extensively inhibited when the base metal ions are much larger than the metal cations in the film; and, in fact, such an effect was observed in the oxidation of a number of copper-base alloys.[6] Table III includes values for the ionic radii, according to Goldschmidt, of the metallic elements included in Tables I and II. Again, elements near the top of the list (smaller diameter) would appear to be more suitable as alloying additions.

It is sometimes possible to improve the oxidation resistance of a base metal by means of small additions of elements which modify the base-metal oxide.[8] Knowing what type of conductor the base-metal oxide is (metal-excess semiconductor, metal-deficit conductor, pure cationic conductor), elements of proper valency relative to the base metal can be selected to reduce the number of lattice defects and, therefore, the diffusion rates of metal cations through the film. For metal-excess semiconductors (such as Nb_2O_5), the oxidation rate is lowered by adding elements of higher valency than the base metal. The oxide of the added element should be largely soluble in the base-metal oxide. (This depends roughly on the difference in the ionic diameters of the base and solute elements; hence, the added elements should possess a smaller atomic diameter.)

Small additions (less than 0.05 percent) of alkaline earth and rare earth elements to various heat-resisting alloys have resulted in remarkable improvements in oxidation resistance, considering the amounts added.[5] Presumably, in nickel-base alloys, such impurities are obstacles to the passage of nickel ions through the scale. It was observed that those elements with greater atomic volumes than nickel oxide prolonged the life while those with smaller atomic volume have no effect. These results suggest the possibility of making small additions of these elements once a fairly good oxidation-resistant alloy has been developed.

The presence of elements that form low-melting point eutectics or compounds with other constituents in the scale of an alloy is to be avoided.[5] For example, 0.04% B in a 30% Cr steel completely destroys the scaling resistance at 1200°C. Also to be avoided are additives which increase the solubility of oxygen in the base metal, for this may lead to penetration by oxygen and consequent embrittlement.

III. EXPERIMENTAL WORK

The objective of the work on niobium-base alloys at NMI during the past year was the development of an oxidation-resistant alloy with high temperature strength and workability. A 1000-fold improvement over the oxidation resistance of unalloyed niobium at temperatures of 2000°F (1093°C) and above was desired. The problem of oxidation resistance was the first to be considered due to the magnitude of the improvement required.

Experimentally, the oxidation tests were designed to provide in as short a time as possible a considerable amount of rough data on the relative merits of alloying additions to niobium. Cube-shaped specimens were cut from arc-melted alloys and heated to 1800°F (980°C) in a muffle furnace with the ends open to air. The time at temperature was 2 hours, the specimen being rapidly heated and rapidly cooled. No attempt was made to control the air flow through the furnace. Results have been expressed as weight gain per unit area per unit time.

Niobium pellets of German origin were obtained from Shield Alloy Corporation. The reported assay of this material is 0.2 w/o Ta (max); 0.2 w/o Ti (max); 0.1 w/o Fe (max); 0.1 w/o C (max). The alloying elements were all approximately 99.9% pure. Arc-melting was used in the preparation of alloys.

In beginning this work, it was thought best to base the selection of alloying elements solely upon solid solubility criteria, and then to correlate the results obtained with the various theoretical considerations mentioned above. The elements with known or expected solid solubility in niobium are listed in Table IV. Since a similar study has been in progress at BMI,[9] care was taken not to duplicate their work except for the cross-checking of several alloys. A number of elements listed in Table IV are enclosed in parentheses. These elements have not been added to niobium in the work at BMI and NMI. Reasons for their exclusion are fairly obvious. Silver, gold, rhenium, and the platinum metals exhibit low affinities for oxygen and form volatile oxides. Gallium oxide is readily reduced. Arsenic, lithium, and germanium are not likely to be practical additions. Hafnium and scandium remain as attractive possibilities, which perhaps merit further consideration. Although the element beryllium is not included in Table IV, it was used as a binary (and ternary) addition. The scope of the alloy studies conducted at BMI and NMI up to the present time is presented in Table V. Chemical analysis of several of the as-cast alloys revealed appreciable losses of materials due to arc melting (see Table VI). In several cases, melting losses resulted in large deviations from the nominal compositions of the alloys.

Tables VII and VIII are devoted to a complete summary of the oxidation-test results obtained at NMI and BMI, respectively. (Only those tests run near 1000°C are reported. BMI also conducted tests at lower temperatures.) The results of the two studies are in fairly good agreement. An exception is the Nb-10 w/o V alloy, for which a low rate was reported by BMI and a high rate by NMI.

Unalloyed niobium oxidizes at a linear rate at 1000°C, the resulting scale offering no protection. The most effective binary additions appear to be titanium, chromium, molybdenum, and aluminum. The best of these additions resulted in little more than a twenty-fold reduction in the oxidation rate of unalloyed niobium.

Table IX is a list of the binary-alloying elements arranged according to their approximate effectiveness in lowering the oxidation rate of unalloyed niobium. Comparison of this list with each of the several theoretical factors discussed earlier in the report yielded no consistent correlations. In other words, present general criteria for predicting whether or not an alloying addition will be beneficial with respect to oxidation resistance do not appear to hold for niobium-base alloys.

A number of ternary alloys have been investigated. However, the best of these (Nb-20 a/o Cr-5 a/o Mo; Nb-20 a/o Ti-5 a/o Be) were not significantly better than the best binary alloys.

An alloy containing Nb-23 w/o Cr-10 w/o Al-15 w/o Si (23.2 a/o Cr-19.4 a/o Al-28.0 a/o Si) was prepared on the basis of the reported success of chromized coatings on low carbon steels.[10,11] This alloy appeared to be quite brittle, but, in preliminary oxidation tests at 980°C and 1200°C, the oxidation resistance was far superior to the results for all other alloys tested. The oxidation rate at 980°C (see Table VII) represents a 1000-fold improvement in the oxidation resistance of unalloyed niobium. At 1200°C, an approximate ten-fold increase in the rate occurred. More careful experiments, however, will be required for an accurate appraisal of this alloy. Also included in the run at 1200°C were specimens of Fe-25 w/o Cr-5 w/o Al alloy, which showed roughly 4 times better oxidation resistance than the Nb-23 w/o Cr-10 w/o Al-15 w/o Si alloy.

IV. TABLES

Table I
Electrical Resistivity of Refractory Oxides

Oxide	Resistivity* Ω- cm	Temperature* °C	Resistivity** Ω - cm	Temperature** °C
BeO	8×10^{13}	1100	10^9	1000
Al_2O_3			10^7	1000
MgO	9×10^{12}	1000	10^5	1000
MnO	10^8	20		
SiO_2	4×10^5	1300	10^6	1000
ThO_2	1.5×10^4	1200		
La_2O_3	10^4	1100		
HfO_2	10^3	1500		
CaO	9.6×10^2	1500	10^7	1000
ZrO_2	3.6×10^2	1200		
CeO_2	3.4×10^2	1200		
SnO_2	6×10	1200		
NiO	2.4×10	1250	10^2	1000
ZnO	5	1300		
UO_2	5×10^2	500		
Cr_2O_3	2.3×10	1000	10^1	1000
TiO_2	8.5	1200		
Nb_2O_3	8.6×10^{-2}	20		
V_2O_3	1.8×10^{-3}	2000		

*Reference 12
**Reference 6

Table II

Free Energies of Formation of Oxides at 1000°C*

(ΔF - cal/mole/atom of O - @ 1300°K)

	$-\Delta F$		$-\Delta F$
CaO	118,450	TiO_2	84,775
ThO_2	116,450	V_2O_3	72,500
Sm_2O_3	115,833	SiO_2	72,200
BeO	112,800	Ta_2O_5	70,780
La_2O_3	112,267	MnO	69,250
SrO	111,200	Nb_2O_5	63,920
Nd_2O_3	110,318	Cr_2O_3	63,600
MgO	109,300	Ga_2O_3	50,500
Y_2O_3	108,333	BaO_2	50,250
Sc_2O_3	104,333	ZnO	48,500
HfO_2	103,275	Fe_3O_4	42,100
UO_2	103,000	WO_2	41,750
ZrO_2	101,350	SnO_2	37,225
Al_2O_3	100,300	CoO	33,300
CeO_2	89,500	NiO	28,560

*Source - Bureau of Mines Bulletin 542 - "Heats and Free Energies of Formation of Inorganic Oxides"

Table III

Ionic Radii of Elements (According to Goldschmidt)

Element	Radius Angstrom	Element	Radius Angstrom
Be	0.34	Zn	0.83
Si	0.39	Zr	0.89
Al	0.57	Mn	0.91
V	0.61	Ca	0.99 - 1.06
Ga	0.62	Ce	1.02
Ti	0.64	U	1.05
Cr	0.65	Y	1.06
Mo	0.66	Th	1.10
Fe	0.67 - 0.83	Sm	1.13
W	0.68	Nd	1.15
Nb	0.69	La	1.22
Cu	0.70	Sr	1.27
Sn	0.71	O	1.32
Ni	0.78	Ba	1.35 - 1.43
Mg	0.78		
Co	0.82		
Sc	0.83		

Table IV

Solubility of Elements in Niobium

Binaries with Nb-Rich Solid Solutions:

(Hf) - 70% at 1000°C

U - Complete solid solubility at 1000°C

Ti - Complete solid solubility at 1000°C

(Re) - 41% at 1200°C

W - Complete solid solubility

Mo - " " "

Ta - " " "

(Rh) - 33% at 1200°C

V - Complete solid solubility

Zr - Approximately 10%

Elements with favorable size factor (<15% difference) compared to Nb:

(Sc), Mg, Sn, (As), (Li), Zn, Mn, (Ag), (Au), Al, (Pt), (Pd), (Os), (Ir), (Ga), (Ru), Cu, Co, Ni, Cr, Fe, (Ge)

( ) Element has not been considered as an additive to Nb to date.

Table V

Scope of Alloy Studies

BINARIES

BMI

1 to 35 a/o Additions: Cr, Mo, Ta, Ti, V, W, Zr
1 to 5 a/o Additions: Co, Fe, Mn, Si

NMI

1 to 30 a/o Additions: Al, Be, Cr, Mg, Sn, Zn, Cu, Ni, U
20 a/o Additions: Co, Fe, Mn, Si, Ti, V

TERNARIES AND MORE COMPLEX ALLOYS:

BMI

Nb - (5 to 24 a/o) Ti -	(1 a/o Al, Si (2 a/o Fe, Co, Ni (5 a/o Mo, W, V (12.5 a/o Zr, Cr, Ta
Nb - (12.5 to 24 a/o) Cr -	(1 a/o Al, Si (5 a/o Mo, W (12.5 a/o Zr, Ta
Nb - 5 a/o Mo -	(1 a/o Al, Si (5 a/o W, V (12.5 a/o Ta

Planned: Other ternaries of Nb with Ti, V, Mo, Cr.
Si additions to best binaries, 0.2 to
5 a/o additions of Be, B to Nb.

NMI

Nb - (5,31 a/o) Cr - (6, 19 a/o) Al
Nb - 20 a/o Ti - 5 a/o Be
Nb - 25 a/o Ti - 10 a/o Al
Nb - 25 a/o Cr - 5 a/o Be
Nb - 23 w/o Cr - 10 w/o Al - 15 w/o Si

Table VI

Chemical Analysis of Arc Melts

Nominal Composition		Actual Composition		Melting Loss %
a/o	w/o	a/o	w/o	
Nb-8 Al	2.47 Al	6.08 Al	1.88 Al	23.9
Nb-8 Be	0.84 Be	3.72 Be	0.39 Be	53.6
Nb-8 Cr	4.64 Cr	6.61 Cr	3.83 Cr	17.5
Nb-1 Cr	0.56 Cr	0.73 Cr	0.41 Cr	26.8
*Nb-25 Ti	14.7 Ti	23.2 Ti	13.6 Ti	7.2
*Nb-25 Cr	15.7 Cr	14.5 Cr	9.1 Cr	42.1
*Nb-25 Mo	25.6 Mo	22.0 Mo	22.5 Mo	12.1
*Nb-5 Al	1.51 Al	<0.7 Al	20.2 Al (a)	>87
*Nb-5 Fe	3.06 Fe	1.88 Fe	1.15 Fe	62.4
*Nb-5 Si	1.56 Si	3.71 Si	1.16 Si	25.8
*Nb-5 Mn	3.02 Mn	0.37 Mn	0.22 Mn	92.7
*Nb-5 Ni	3.22	2.33 Ni	1.50 Ni	53.4

*BMI alloys - see BMI-1076, Feb., 1956, p.70

(a) Spectrographic analysis

Table VII

NMI Oxidization Test Results

Alloy Composition (Nominal)	Weight Gain for 2 Hours at 980°C (mg/cm^2/hr)	Weight Gain for 16 Hours at 980°C (mg/cm^2/hr)
Unalloyed Nb	43	Completely Oxidized
Nb-1 a/o Al	45	
Nb-2 a/o Al	51	
Nb-4 a/o Al	48	
Nb-8 a/o Al	44	
Nb-20 a/o Al	10, 20	
Nb-1 a/o Be	35	
Nb-2 a/o Be	33	
Nb-4 a/o Be	37	
Nb-8 a/o Be	41	
Nb-16 a/o Be	35	
Nb-Cr 1 a/o	25	
Nb-Cr 2 a/o	32	
Nb-Cr 4 a/o	25	
Nb-Cr 8 a/o	39	
Nb-Cr 16 a/o	53	
Nb-Cr 25 a/o	6	
Nb-Cr 32 a/o	3	8
Nb-25 a/o Ti	4	2
Nb-20 w/o Cr-6 w/o Al	4	2
Nb-10 w/o Cr-2 w/o Al	4	
*Nb-23 w/o Cr-10 w/o Al-15 w/o Si	0.6	0.04
Nb-10 w/o V	57, 82	
Nb-20 a/o Ti-5 a/o Be	2	
Nb-25 a/o Ti-10 a/o Al	4	1
Nb-25 a/o Cr-5 a/o Be	86	
Nb-5 a/o Cu	50	
Nb-20 a/o Cu	128	
Nb-5 a/o Mg	35	
Nb-20 a/o Mg	54	
Nb-5 a/o Ni	39	
Nb-20 a/o Ni	32	
Nb-5 a/o Sn	23	
Nb-20 a/o Sn	Brittle as-cast	
Nb-5 a/o U	60	
Nb-20 a/o U	75	
Nb-5 a/o Zn	54	
Nb-20 a/o Zn	56	
Nb-20 a/o Fe	32	
Nb-20 a/o Mn	41	
Nb-20 a/o Si	80	
Nb-20 a/o Co	23	

*Rate obtained for this alloy at 1200°C for 2½ hours approximately 0.75 mg/cm^2/hr
Rate obtained for this alloy at 1200°C for 10 hours approximately 0.28 mg/cm^2/hr
Rate obtained for Fe-25 w/o Cr-5 w/o Al alloy for 10 hrs. approx. 0.074 mg/cm^2/hr at 1200°C

Table VIII

BMI Oxidation Test Results (Sept. '55 - Apr. '56)*

Alloy Composition (Nominal)	Wt. Gain at 1000°C ($mg/cm^2/hr$)
Unalloyed Nb	25.8, 38.4, 30.8, 24.2, 24.2
Nb-0.7 a/o Al	19.4
Nb-1 a/o Cr	33.1
-5 a/o Cr	28.1
-10 a/o Cr	26.2
-25 a/o Cr	6.1
-35 a/o Cr	22.3
Nb-0.2 a/o Co	43.8
-1 a/o Co	37.6
-5 a/o Co	38.5
Nb-0.2 a/o Fe	35.6
-1 a/o Fe	25.0
-5 a/o Fe	25.0
Nb-0.2 a/o Mn	21.8
-1 a/o Mn	22.1
-5 a/o Mn	23.9
Nb-1 a/o Mo	13.2
-5 a/o Mo	4.6
-7.5 a/o Mo	10.4
-10 a/o Mo	10.1
-25 a/o Mo	42.5
Nb-0.2 a/o Ni	30.3
-1 a/o Ni	58.5
-5 a/o Ni	46.3
Nb-0.2 a/o Si	21.4
-1 a/o Si	46.5
-5 a/o Si	103.8
Nb-1 a/o Ta	68.2
-5 a/o Ta	25.5
-10 a/o Ta	20.3
-25 a/o Ta	61.3
Nb-1 a/o Ti	26.0
-5 a/o Ti	15.7
-10 a/o Ti	7.7
-25 a/o Ti	1.9
-35 a/o Ti	4.3

Table VIII
(continued)

Alloy Composition (Nominal)	Wt. Gain at 1000°C (mg/cm^2/hr)
Nb-1 w/o V	13.8
-5 w/o V	4.6
-10 w/o V	3.5
-25 w/o V	193
Nb-1 w/o W	59
-5 w/o W	54
-10 w/o W	26
-25 w/o W	94
Nb-1 a/o Zr	71.0
-5 a/o Zr	135
-10 a/o Zr	101
-25 a/o Zr	49.5
-35 a/o Zr	30.0
Nb-12.5 a/o Cr - 12.5 a/o Ta	34.0
-12.5 a/o Cr - 12.5 a/o Zr	37.0
-20 a/o Cr - 5 a/o Mo	1.7
-20 a/o Cr - 5 a/o W	10.2
-24 a/o Cr - 1 a/o Al	10.8
-24 a/o Cr - 1 a/o Si	23.6
Nb-5 a/o Mo - 1 a/o Al	3.6
-5 a/o Mo - 1 a/o Si	15.4
-5 a/o Mo - 5 a/o V	3.15
-5 a/o Mo - 5 a/o W	22.0
-5 a/o Mo - 12.5 a/o Ta	4.4
Nb-5 a/o Ti - 5 a/o Mo	7.1
-10 a/o Ti - 5 a/o Mo	3.9
-10 a/o Ti - 10 a/o Mo	3.3
-12.5 a/o Ti - 12.5 a/o Cr	3.9
-12.5 a/o Ti - 12.5 a/o Ta	7.9
-12.5 a/o Ti - 12.5 a/o Zr	10.6
-15 a/o Ti - 5 a/o Mo	3.1
-20 a/o Ti - 5 a/o Mo	2.7
-20 a/o Ti - 5 a/o V	2.8
-20 a/o Ti - 5 a/o W	2.8
-24 a/o Ti - 1 a/o Al	4.0
-24 a/o Ti - 1 a/o Si	3.9
-23 a/o Ti - 2 a/o Co	3.7
-23 a/o Ti - 2 a/o Fe	3.6
-23 a/o Ti - 2 a/o Ni	7.6

*Sources: BMI-1043, 1050, 1057, 1062, 1070, 1076, 1080, 1088

Table IX

Effect of Binary Additions on Oxidation Rate of Unalloyed Niobium

(Arranged in order of decreasing resistance to oxidation)

<10% Binary Addition	>10% Binary Addition
Mo	Ti
Ti	Cr
Sn	Al
Ta	Co
Si (very small amount)	
Mn	
Fe	Ni
Cr	Fe
Mg	Be
Be	Mn
Ni	Nb (unalloyed)
Nb (unalloyed)	Zr
Al	
Co	
Cu	Mo
Zn	Mg
Si	Zn
W	U
U	Ta
Zr	Si
	W
	Cu
	V

V. REFERENCES

1. E. Scheil and E. H. Shulz, "Hitzebestandige Chrom-Aluminum Stahle", Archiv. fuer Eisenhuettenwesen, Vol. 6, 1932-33, p. 21.

2. E. Scheil and E. Kiwit, "Einfluss von Legierungszusammensetzung auf das Zundern des Eisens", Archiv. fuer Eisenhuettenwesen, Vol. 9, 1935-36, p. 405.

3. E. Scheil, "Uber das Zundern von Metallen und Legierungen", Zeitschrift fuer Metallkunde, Vol. 29, 1937, p. 209.

4. K. W. Froehlich, "Die Zunderung von reinum und legiertum Kupfer", Zeitschrift fuer Metallkunde, Vol 28, 1936, p. 368.

5. B. Lustman, "The Resistance of Metals to Scaling", Metal Progress, Vol. 50, 1946, p. 851.

6. L. E. Price and G. J. Thomas, "Oxidation-Resistant Copper Alloys", Journal, Institute of Metals, Vol. 63, 1938, p. 21.

7. O. Kubaschewski and B. E. Hopkins, <u>Oxidation of Metals and Alloys</u>, Butterworths Scientific Publications, London, 1953, p. 151.

8. Ibid, p. 130.

9. Battelle Memorial Institute Reports: 1043, 1050, 1057, 1062, 1070, 1076, 1080, 1088.

10. Galmiche, P., Rev. Metall, Vol. 47, 1950, p. 192.

11. R. Samuel and N. Lockington, Metal Treatment, Vol. 19, 1952, p. 31.

12. E. M. Sherwood, <u>High Temperature Technology</u>, Chapter 2, John Wiley & Sons, Inc., New York, 1956, p. 58.

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