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SELECTED PROPERTIES OF VANADIUM ALLOYS
FOR REACTOR APPLICATION

by

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Final Report - Metallurgy Program 4.10.10

May, 1957

Portions of the material in this report have appeared
in the following Metallurgy Division Quarterly Report:

ANL-5465 pp. 33-35 June, 1955

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Operated by The University of Chicago
under
Contract W-31-109-eng-38

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SELECTED PROPERTIES OF VANADIUM ALLOYS FOR REACTOR APPLICATION

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ABSTRACT

Selected vanadium-base alloys have been investigated as to tensile and creep strength, corrosion resistance, and thermal conductivity at elevated temperatures for the purpose of making a preliminary evaluation of suitability for use as fuel-element jacketing materials for sodium-cooled reactors.

Results indicate the preliminary feasibility of these alloys from all viewpoints under examination and suggest the desirability of studying fabrication problems of alloys and improved reduction methods for vanadium metal.

INTRODUCTION

The operation of nuclear power reactors at higher temperatures is a desirable goal from the standpoint of over-all efficiency in the matter of producing steam for driving turbines. The use of liquid sodium as a heat transfer medium, among other things, directly removes one limitation to higher temperature operation by eliminating the extreme pressurizing necessary in water-cooled reactors. The use of sodium also permits conversion of U^{238} to plutonium for additional reactor fuel because of its non-moderating properties. Higher conversion efficiencies in these fast reactors are promoted by higher power densities in the fuel material, which in turn require higher fuel temperatures.

To utilize these advantages of higher temperature operation, fuel elements need to be developed which will withstand these temperatures. Ceramic fuel materials are able to meet the temperature requirements, but have certain classical disadvantages in brittleness and low thermal conductivity. If metallic fuel elements are preferred, the most obvious limitations are the low melting points of the eutectic compositions of uranium with some of the more common associated cladding or jacketing materials, such as stainless steel. When uranium and the iron in stainless steel are in mechanical contact, temperatures above about 725° C at the interface will cause them to melt down together, destroying the fuel element. Since coolant outlet temperatures are considerably lower than metal interface temperatures, the coolant temperature limit is much lower than 725° C.

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To lift this limitation, other metals are proposed which have higher melting eutectic compositions with uranium. Among these materials is vanadium, which was selected as providing perhaps the most reasonable compromise with other necessary properties, as outlined in the next section. Vanadium forms a eutectic with uranium at 1040° C. If other requirements could be met, the use of vanadium as a jacketing material might be capable of raising the limiting temperature for reactor operation by over 300° C.

SELECTION CRITERIA OF FUEL ELEMENT PROTECTIVE MATERIALS IN A SODIUM MEDIUM

Aside from compatibility with uranium, other requirements are (1) good resistance to deformation at service temperatures, (2) good resistance to sodium corrosion, (3) acceptable values of thermal conductivity, and (4) ease of fabrication, consistent with strength.

Resistance to Deformation

Perhaps the best measure of resistance to deformation at elevated temperature is provided by creep and stress rupture tests, especially if no cyclic stress components are important. Because of the difficulty and expense connected with these tests, data are meager; the inclination is to perform elevated temperature tensile tests instead, particularly if only a rough indication of strength is required.

Figure 1 shows, among other things, a comparison of the tensile strength of unalloyed vanadium, annealed at 900° C, as reported by Rostoker, McPherson, and Hansen⁽¹⁾ and of Type 347 stainless steel.⁽²⁾ These curves show that the use of unalloyed vanadium in place of Type 347 stainless steel for structural components would necessitate some "beefing up" of structural components over more conventional steel designs, resulting in a higher ratio of structural material to fuel material, thereby with reduced core efficiency. It is desirable, therefore, to develop the high temperature strength by suitable alloying.

Corrosion Resistance

Other materials of the refractory group, zirconium, titanium, niobium, tantalum, tungsten and molybdenum, have been indicated⁽³⁾ to possess good corrosion resistance to sodium as high as 600° C and possibly higher. Although not conclusive, this provided some evidence to justify the belief that vanadium might prove likewise.

Like molybdenum, vanadium forms a low melting oxide (V_2O_5 ; M. P. 670°C), but there are important differences in favor of vanadium in a sodium atmosphere. Efforts are usually made for other reasons to keep the oxygen content low in a sodium-cooled reactor. Moreover, the free energies of formation of the vanadium oxides are such that the stable oxides

VO and V_2O_3 should form, and the unstable oxide V_2O_5 should not form in sodium. This is an ideal condition, in that the stable oxides might be expected to provide a protective barrier against further corrosion and prevent self-welding of parts, as might occur if all oxides were wiped clean from the metal surface.

Figure 2, compiled from Bureau of Mines data, (4) shows free energies of formation per atom of oxygen in the oxides of a number of metals for mutual comparison. Oxides with values of free energy above Na_2O on the graph will not form in a medium of sodium; those situated below will form at the expense of the oxygen in Na_2O , reducing it to sodium. It will be observed on this basis that the oxides of (1) molybdenum will not form, (2) uranium, UO_2 and UO_3 , will form, (3) niobium will form above about $400^\circ C$, and (4) vanadium, stable VO and V_2O_3 , will form and unstable V_2O_5 will not form. V_2O_4 , another high melting oxide, would not be expected to form until above about $750^\circ C$. The position of vanadium in terms of sodium corrosion would therefore be expected to be favorable in the range of temperatures (650° to $800^\circ C$) considered at present.

Thermal Conductivity

If the thermal conductivity of cladding metal A is twice as high as that of metal B, metal A could be made twice as thick as metal B, for purposes of strength, and still deliver as much heat away from the core material. Some penalty would be paid in adverse ratio of structural material to fuel material. However, conversely, if both metals were equally strong, like thicknesses of cladding metal A would deliver much more useful heat to the turbines than metal B, with the same temperature of the fuel-jacket interface.

Alloying of a metal for purposes of strength involves interrupting the crystalline lattice with enough irregularity to provide strength. Unfortunately, the same operation reduces the mean free path of electrons and of lattice vibrations through the metal, which in turn reduces the thermal conductivity. Development of high strength, therefore, is accompanied by a substantial loss of thermal conductivity, reckoned on the basis of a pure metal.

Alloying of materials like zirconium and titanium, which, even in the pure state, are poorer heat conductors than either uranium or stainless steel, result in unacceptably low thermal conductivity in the alloyed form. (5) This leaves the metallurgist with two choices: (1) selection of a metal with sufficient strength to do the task in its pure state, or (2) choosing a material with conductivity standards much higher than accepted, so that alloying will not reduce the conductivity below the selected standard.

Table I gives the approximate room temperature thermal conductivity for some relevant metals. Although conductivity data at elevated temperatures would be more pertinent, the room temperature values are sufficient to provide adequate comparison. Using a thermal conductivity value of $0.040 \text{ cal-cm/cm}^2 \text{ sec } ^\circ \text{C}$, approximately that of stainless steel as a standard, vanadium qualifies, although tantalum and molybdenum would be much better from a viewpoint of thermal conductivity alone.

Ease of Fabrication

While the present report does not deal with this phase of the investigation, it is worth while to note that the most desirable material in the world is useless if it cannot be fabricated. On the other hand, materials are often rejected because the proper technique for their fabrication has not been developed. If high strength is necessary in a material, this requirement alone may be to some extent incompatible with ease of fabrication.

It should be pointed out that vanadium binary alloys, with titanium up to 10 per cent have been rolled to 95 per cent cold reduction without edge cracking. This gives basis for optimism that suitable techniques may be developed for the other alloys investigated in this report.

The balance of the report will describe efforts to select alloys of vanadium for strength consistent with the aims described above. No problems relating to availability, cost, or fabricability will be considered.

EXPERIMENTAL DATA

Strength at Elevated Temperatures

Experimental work reported under the heading of elevated temperature strength was performed by Armour Research Foundation under Argonne Research and Development Subcontract 31-109-38-641. More detailed information will be contained in a report issued directly by Armour.

Previous work, also by Armour,^(1,6) had shown good ductility and forgeability for binary base alloys of vanadium-titanium in contrast to other systems, and it was decided on the basis of these results that information on high temperature strength would be useful on this group of alloys. Aside from one silicon alloy, the investigations were therefore confined to the vanadium-titanium binary and selected ternaries based on it.

Vanadium metal, 99.7+ per cent pure, was obtained from Electro Metallurgical Company and titanium, 99.7+ per cent pure, from E. I. DuPont de Nemours & Company. Melting was accomplished in a non-consumable electrode arc furnace. Resulting ingots were heated to temperatures as high as 1400°C (2550°F) for press and hammer forging to $1/2$ and/or $3/4$ -inch

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diameter bars. Unalloyed vanadium was forged at 980° C (1800° F). Results of forging for some of these alloys are given in Table II. More extensive forging procedures might have resulted in a larger number of acceptable compositions. Part of the forgings was retained by Armour for tensile and stress-rupture testing, and another part was sent to Argonne for corrosion and thermal conductivity testing. Machining of the specimens was difficult, because of an outer hard case, which had to be ground. After the case was penetrated, machining was possible, but since grinding operations were already set up, specimens were finished in this manner.

Tensile and stress-rupture specimens were protected by a helium atmosphere. Stress-rupture tests were limited to binary alloys of vanadium and titanium. Tensile data, as reported by Armour, are given in Tables III, IV, and V with data for Type 347 stainless steel included for comparison. Three selected compositions have been plotted on Figure 1. Since elevated temperature tensile strength, as measured by standard tensile machines, is sensitive to crosshead speed, the value of 0.05 inch per minute was adopted for all tests to conform with the stainless steel data. Stress-rupture data on the vanadium-titanium binary alloys are plotted in Figure 3.

Corrosion Resistance

Four series of static corrosion tests on vanadium alloys, three in sodium and one in water, were made by the Reactor Engineering Division at Argonne. Behavior in water was not strictly pertinent to the subject at hand. However, since the alloys were already prepared, it represented the acquisition of additional information easily available with little additional effort. Tests were made as follows: (1) in sodium, oxygen content unknown, 257 hours at 613° C, followed by 760 hours at 802° C; (2) in sodium, with Na₂O above 0.2 w/o, 936 hours at 800° C; (3) in sodium, with Na₂O below 0.001 w/o, 288 hours at 700° C; and (4) in degassed water, 327 hours at 360° C (680° F). Data from the four series of tests above are given in Tables VI, VII, VIII, and IX, respectively.

No dynamic loop corrosion tests have been made, nor have any tests specifically been directed toward evaluating the effect of oxygen. However, metallographic sections were made (see Appendix) of the samples in series (2) to determine the method of attack by the sodium. Findings of these tests are reported in the discussion, and micros are shown in Figure 5 of the Appendix.

Thermal Conductivity

Tests of thermal conductivity, of a preliminary nature, were made by the Argonne Chemistry Division. These tests served to (1) check the original postulate that vanadium and its alloys have fairly high thermal conductivity, and (2) evaluate qualitatively how much titanium or silicon

could be tolerated in the binary ¹⁰ composition without undue reduction of heat transfer properties. Results are given in Table X and plotted in Figure 4. A portion of these data has been previously reported.⁽⁷⁾ Further work on thermal conductivity, however, would be desirable if closer composition limits were to be selected by designers.

DISCUSSION OF RESULTS

Tensile, yield, and creep strengths of vanadium alloys as a class have been shown by the data in Tables III, IV, and V, and in Figures 1 and 3 to be higher than the corresponding values for Type 347 stainless steel by very wide margins. A single exception is the 1 w/o Si alloy, which is roughly equivalent to stainless steel in tensile strength. The binary alloys containing 5, 10, and 20 w/o titanium possess a 100-hour rupture life of about 50,000 psi at 650°C, as compared to 27,000 psi for Type 347 stainless steel. The extremely high strength of the binary and ternary alloys would allow very thin jackets on fuel elements, so much so that problems of fabricating sufficiently thin jackets to take advantage of this property are thereby suggested. If means could be found to use jackets of these alloys of perhaps 4 or 5-mil thickness, it might be found that restraint of the fuel material would still be quite adequate for stability.

If high ductility at service temperatures is an important design consideration, the binary silicon alloy could be specified without reducing tensile strength below the level of stainless steel. However, this alloy suffers from lack of ductility at room temperature.

In spite of some divergence of corrosion data between Tables VI and VII at 800°C, probably from lack of oxygen control, the statement can be made that vanadium alloys are generally corrosion resistant to sodium to 700°C and nonresistant to degassed water at moderately elevated temperatures. It is evident from Table VIII that unalloyed vanadium and at least nine of its alloys have excellent corrosion resistance to static sodium at 700°C when Na₂O is kept down to 10 ppm in the system.

Experiments are necessary to establish the degree of oxygen control necessary to prevent the type of catastrophic corrosion shown in Table VII at 800°C, where excessive Na₂O was present. The metallographic examination (see Appendix) subsequent to the corrosion test results reported in Table VII showed intergranular attack for all specimens, plus a general diffusional attack on the 10 w/o Ti alloys, but which was missing in the 2.5 w/o Ti alloys. It is not certain whether or not this intergranular attack indicates formation of the unstable V₂O₅ in the presence of excessive oxygen, with a subsequent leaching out of the liquid oxide.

The thermal conductivity of vanadium and its binary alloys in the ranges studied in this report are high compared to materials like zirconium, uranium, and stainless steel, as shown by Figure 4. Perhaps as much as 30 per cent of titanium can be added as a binary without reducing the thermal conductivity below that of Type 347 stainless steel. Aluminum as a ternary addition appears to reduce the value drastically. More work should be done to determine the conductivity of other ternary alloys.

It is also pointed out that if the strength advantage of these alloys can be exploited by the use of thin jackets or cladding, further advantage may be gained in heat transfer properties.

Fabricability, availability, and cost of present reduction methods of pure vanadium are subjects for further investigation in regard to feasibility of use of these materials in sodium-cooled reactors.

ACKNOWLEDGEMENTS

Acknowledgement is hereby made for the section of work performed by members of the Armour Research Foundation, for the corrosion testing to J. H. Monaweck, C. R. Breden, and R. A. Stella of Argonne Reactor Engineering Division, for thermal conductivity work to J. L. Weeks of the Argonne Chemistry Division, and to R. M. Scott for metallographic examination.

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Table I

APPROXIMATE ROOM TEMPERATURE THERMAL
CONDUCTIVITY OF CERTAIN METALS

Material	Approximate Thermal Conductivity at Room Temperature	
	cal-cm/cm ² sec °C	BTU-ft/ft ² hr °F
Titanium	0.037	9
347 SS	0.039	9.5
Zirconium	0.047	11.5
Uranium	0.062	15
Vanadium	0.084	20
Tantalum	0.130	32
Molybdenum	0.350	84

Table II

SOME RESULTS OF FORGING VANADIUM ALLOYS

Alloy Composition (w/o)	Remarks
V-10 Ti-1 Mo	Good
V-10 Ti-0.5 Si	Good
V-10 Ti-1 Ta	Good
V-10 Ti-3 Ta	Good
V-10 Ti-1 Nb	Good
V-10 Ti-3 Nb	Good
V-10 Ti-1 Cu	Bars Seamed
V-2.5 Ti	Surface Imperfections
V-2.5 Ti-1 Si	Surface Imperfections
V-10 Ti-3 Mo	Cracked
V-10 Ti-0.5 Be	Cracked
V-10 Ti-1 Be	Cracked
V-10 Ti-3 Cu	Cracked
V-10 Ti-1 Sn	Cracked
V-10 Ti-3 Sn	Cracked

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Table III

TENSILE DATA AT ROOM TEMPERATURE FOR VANADIUM-BASE ALLOYS

(Annealed at 650° C for 2 days and water quenched)

Alloy (w/o)	Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Reduction of Area (%)
V-1 Si	46,000		0	0
V-2.5 Ti	90,160		12	24
V-5 Ti	78,500		26	78
V-10 Ti	91,570		27	66
V-10 Ti-1 Mo	88,400	69,400	11	25
V-10 Ti-1 Ta	92,400	70,000	21	41
V-10 Ti-3 Ta	94,400	72,000	23	43
V-10 Ti-0.5 Si	94,800	76,000	12	27
V-10 Ti-1 Si	93,000		30	38
V-10 Ti-1 Nb*	84,600	63,200	11	20
V-10 Ti-3 Nb	97,600	64,500	22	38
V-20 Ti	101,000		29	49

*Imperfection in specimen.

Table IV

TENSILE DATA AT 650° C FOR VANADIUM-BASE ALLOYS

(Annealed at 650° C for 2 days and water quenched)

Alloy (w/o)	Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Reduction of Area (%)
V-1 Si	43,400	33,400	62	80
V-2.5 Ti	68,200	48,600	17	36
V-2.5 Ti-1 Si	78,400	60,000	13	25
V-5 Ti	57,000			
V-10 Ti	74,200	52,000	22	43
V-10 Ti-1 Mo	77,200	60,000	22	46
V-10 Ti-1 Ta	75,400	55,000	24	52
V-10 Ti-3 Ta	78,800	57,000	25	55
V-10 Ti-0.5 Si	77,600	58,000	24	69
V-10 Ti-1 Si	90,000	66,000	17	52
V-10 Ti-1 Nb*	80,400	58,000	15	41
V-10 Ti-3 Nb	86,000	64,000	21	48
V-20 Ti	86,500			
Stainless Steel (Type 347)	51,200	41,000	46	71

*Imperfection in specimen.

Table V

TENSILE DATA AT 800° C FOR VANADIUM-BASE ALLOYS

(Annealed at 800° C for 24 hrs and water quenched)

Alloy (w/o)	Tensile Strength (psi)	Yield Strength (psi)	Elongation (%)	Reduction of Area (%)
V-1 Si*	20,800	18,400	63	91
V-2.5 Ti	45,000	40,400		33
V-2.5 Ti-1 Si*	44,400	38,000	25	71
V-5 Ti	45,500			
V-10 Ti	57,500			
V-10 Ti-1 Mo	54,600	41,000	17	25
V-10 Ti-1 Ta*	47,000			
V-10 Ti-3 Ta	54,400	40,000	10	19
V-10 Ti-0.5 Si	56,200	42,000	40	65
V-10 Ti-1 Si	63,200	48,800	28	71
V-10 Ti-1 Nb*	55,200	41,600	13	33
V-10 Ti-3 Nb	58,400	46,400	28	60
V-20 Ti	70,250			

*Imperfection in specimen.

Table VI
RESULTS OF PRELIMINARY CORROSION TESTS IN STATIC SODIUM AT 613° C AND 802° C
(Na₂O content unknown)

Composition (w/o)	Corrosion Rate at 613° C (mg/cm ² mo)	Remarks	Corrosion Rate at 802° C (mg/cm ² mo)	Remarks
Vanadium (unalloyed)	- 0.2	Satin gray tarnish	- 1.3	Dull gray tarnish
Vanadium (unalloyed)	-	Satin gray tarnish	+ 0.34	Dull gray tarnish
V-5 Ti	- 0.52	Satin gray tarnish - one edge nicked	- 0.92	Dull gray tarnish
V-5 Ti	- 0.13	Satin gray tarnish	- 0.72	Dull gray tarnish
V-10 Ti	- 0.26	Satin gray tarnish	- 0.31	Dull gray tarnish
V-10 Ti	- 1.03	Satin gray tarnish	- 0.35	Dull gray tarnish
V-20 Ti	- 0.54	Mottled satin gray tarnish	+ 0.23	Dull gray tarnish
V-20 Ti	+ 1.52	Mottled satin gray tarnish	+ 0.21	Dull gray tarnish
V-10 Ti-5 Al	-	Black lustrous tarnish	- 2.4	Black film covering lustrous black tarnish (loose non-adherent film)
V-10 Ti-5 Al	- 0.12	Black lustrous tarnish	- 1.5	Black film covering lustrous black tarnish (loose non-adherent film)
V-40 Ti-5 Al	- 0.25	Black lustrous tarnish	- 0.17	Finely mottled brown and gray tarnish
V-40 Ti-5 Al	- 0.38	Black lustrous tarnish	- 0.04	Finely mottled brown and gray tarnish
V-1 Si	-	Gray satin tarnish	+ 0.04	Dull dark gray tarnish
V-1 Si	+ 0.13	Gray satin tarnish	- 0.08	Dull dark gray tarnish
V-3 Si-2.5 Zr	- 1.04	Mottled gray and black tarnish	- 2.2	Dull gray tarnish
V-3 Si-2.5 Zr	- 1.04	Mottled gray and black tarnish	- 3.0	Dull gray tarnish
Nickel	- 0.58	Satin silver tarnish - one edge nicked	- 2.6	Satin silver tarnish
Nickel	- 1.22	Satin silver tarnish - one edge nicked	- 2.7	Satin silver tarnish
Nickel	- 0.72	Satin silver tarnish - one edge nicked	- 2.1	Satin silver tarnish
Nickel	- 0.97	Satin silver tarnish - one edge nicked	- 2.1	Satin silver tarnish
304 SS	- 0.49	Mottled dark tarnish and machined surface	None	Mottled silver and black tarnish
304 SS	- 0.751	Mottled dark tarnish and machined surface	- 0.21	Mottled silver and black tarnish
304 SS	- 0.886	Mottled dark tarnish and machined metal surface	+ 0.09	Mottled silver and black tarnish
304 SS	- 0.342	Mottled dark tarnish and machined metal surface	- 0.16	Mottled silver and black tarnish

Table VII

RESULTS OF CORROSION TESTS IN STATIC SODIUM AT
800°C FOR 936 HOURS(Na₂O in excess of 0.2 w/o)

Composition (w/o)	Corrosion Rate (mg/cm ² mo)	Per cent Weight Loss
V-10 Ti-0.5 C	11	2.2
V-10 Ti-3 Ta	23	4.3
V-2.5 Ti-1 Si	23	5.9
V-10 Ti-1 Nb	74	16.3
V-10 Ti-1 Si	171	46
V-10 Ti-3 Nb	304	58
V-10 Ti-1 Mo	77	16.7
V-10 Ti-1 Cu	25	5.2
V-10 Ti-1 Ta	22	4.2
V-2.5 Ti	109	23
V-10 Ti-0.5 Si	88	37
SS 347	1	.09
Ni	3	- .33

Table VIII

RESULTS OF CORROSION TESTS IN STATIC SODIUM AT
700°C FOR 288 HOURS(Na₂O, 0.001 %)

Composition (w/o)	Per cent Weight Gain	Remarks
Vanadium (unalloyed)	0.10	Unattacked
V-2.5 Ti	0.11	Good
V-5 Ti	0.14	Very Good
V-10 Ti	0.26	Cracked scale on top and side
V-20 Ti	0.45	Scale on top and side
V-1 Si	0.04	Very Good
V-2.5 Ti-1 Si	0.07	Good
V-5 Ti-5 Cr	0.08	Good
V-10 Ti-0.5 C	- 0.46	Good
V-10 Ti-0.5 Si	0.08	Cracks around edge. Surface oxide scrapes off.
V-10 Ti-1 Si	0.19	Good. Light film on surface scrapes off.
V-10 Ti-1 Cu	0.28	Slight etching and pitting in spots.
V-10 Ti-1 Mo	0.26	Slight scale on side. Top and bottom good.
V-10 Ti-1 Nb	0.17	Good. No scaling
V-10 Ti-1 Ta	0.15	Sealed all over. Thin scale
V-10 Ti-3 Nb	0.19	Good
V-10 Ti-3 Ta	0.19	Good
V-10 Ti-5 Al	0.25	Thin scale top, bottom, and sides.
V-40 Ti-5 Al	0.69	Cracked and scaled.

Table IX

RESULTS OF CORROSION TESTS IN STATIC DEGASSED WATER AT 360°C FOR 327 HOURS

(All samples in one autoclave)

Composition (w/o)	Test Period		Corrosion Rate (mg/cm ² /mo)	Remarks
	No.	Hr.		
V-10 Ti-1 Si	1	329	+0.684	Adherent black coating.
	2	327	+0.585	Adherent black coating.
V-10 Ti-0.5 C	1	329	+0.411	Adherent black coating.
	2	327	+0.378	Adherent black coating.
V-10 Ti-1 Nb	1	329	+0.718	Adherent dark gray to black coating.
	2	327	+0.825	Loose black and gray coating.
V-2.5 Ti-1 Si	1	329	+0.479	Heavy loose gray scaly black coating over adherent black tarnish.
	2	327	+1.79	Loose scaly gray-black coating.
V-10 Ti-3 Ta	1	329	+0.616	Part of sample has loose gray scaly black coating over adherent black tarnish. Other part of sam- ple has adherent black coating.
	2	327	+0.757	Loose scaly gray-black coating.
V-10 Ti-1 Mo (pipe thru center)	1	329	-0.308	Loose black coating.
	2	327	+0.172	Loose black coating; one pit.
V-10 Ti-3 Nb	1	329	+0.274	Loose black coating.
	2	327	±0.000	Loose gray-black coating.
V-10 Ti-0.5 Si	1	329	+0.342	Loose black coating.
	2	327	+1.45	Loose black coating.
V-2.5 Ti	1	329	+0.855	Heavy loose black coating over adherent black tarnish.
	2	327	+1.93	Loose black coating.
V-10 Ti-1 Ta	1	329	-0.444	Loose black coating over adherent black tarnish.
	2	327	-2.58	Loose black coating.
V-10 Ti-1 Cu (cracked)	1	329	-2.70	Loose black coating.
	2	327	-3.44	Loose black coating.

Table X

THERMAL CONDUCTIVITY OF VANADIUM AND CERTAIN
VANADIUM-BASE ALLOYS AT 70°C

(Reference No. 7)

Composition (w/o)	Thermal Conductivity ^(a) (cal cm/cm ² sec °C)
Vanadium (unalloyed)	0.084
V-5 Ti	0.070
V-10 Ti	0.058
V-20 Ti	0.047
V-10 Ti-5 Al	0.031
V-40 Ti-5 Al	0.024
V-1 Si	0.064
V-3 Si-2.5 Zr ^(b)	0.050

^aLast figure rounded.^bFlaw in side of specimen.

FIGURE I
TENSILE STRENGTH OF CERTAIN VANADIUM ALLOYS AT
ELEVATED TEMPERATURES

FIGURE 2
FREE ENERGY OF FORMATION OF CERTAIN METALLIC OXIDES
(See Ref. No.4)

FIGURE 3
STRESS RUPTURE CURVES FOR VANADIUM-TITANIUM ALLOYS

FIGURE 4
EFFECT OF COMPOSITION ON THERMAL CONDUCTIVITY
OF VANADIUM ALLOYS

APPENDIX

METALLOGRAPHY REPORT NO. 2523 ON SAMPLES FOLLOWING
CORROSION TEST REPORTED IN TABLE VII (800° C)

Specimen Number	Composition (w/o)	Section	Micro No.	Surface Preparation	Etchant	Illumination	Mag.
1	V-10 Ti-0.5 C	Long	20435	Etched	*	B. F.	250X
			20436	Etched	*	B. F.	500X
2	V-10 Ti-3 Ta	Long	20437	Etched	*	B. F.	250X
			20438	Etched	*	B. F.	500X
3	V-2.5 Ti-1 Si	Long	20439	Etched	*	B. F.	250X
4	V-10 Ti-1 Nb	Long	20440	Etched	*	B. F.	250X
			20441	Etched	*	B. F.	500X
5	V-10 Ti-1 Si	Long	20442	Etched	*	B. F.	250X
			20459	Etched	*	B. F.	1000X
6	V-10 Ti-3 Nb	Long	20443	Etched	*	B. F.	500X
			20439	Etched	*	B. F.	250X
7	V-10 Ti-1 Mo	Long	20444	Etched	*	B. F.	250X
			20445	Etched	*	B. F.	500X
8	V-10 Ti-1 Cu	Long	20458	Etched	*	B. F.	100X
9	V-10 Ti-1 Ta	Long	20446	Etched	*	B. F.	100X
			20447	Etched	*	B. F.	250X
10	V-2.5 Ti	Long	20448	Etched	*	B. F.	250X
			20449	Etched	*	B. F.	500X
11	V-10 Ti-0.5 Si	Long	20460	Etched	*	B. F.	100X

*Etchant: 80 ml Methanol; 20 ml H₂SO₄; 3 drops H₂O (A high vanadium electro-polish). This was followed by an AgNO₃ + HF + H₂O swab etching.

A metallographic examination was conducted on eleven vanadium-base ternary alloy samples to help evaluate the method of corrosion attack in sodium.

The most striking effect of alloy content was observed for samples 3 and 10 which contained only 2.5 w/o titanium. These samples showed the least amount of edge effect.

In all samples except 3 and 10, etching brought out an intergranular attack plus a general diffusional attack at the exposed surfaces of the samples.

This critique shows photomicrographs at 100X and 250X for observing the edge effects, and at approximately 500X and 1000X for observing the grain structure.

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Figure 5. Photomicrographs of Vanadium Alloys after 936 Hours Exposure to Sodium at 800°C with Na₂O Greater than 0.2 w/o.

Sample (1) V-10 Ti-0.5 C

(a)

Micro 20,435

250X

Edge effect; grains are anisotropic with polarized light. Preferential etching has darkened some grains more than others. Under bright field illumination the grains near the edge are relatively free of the peppery constituent found in the center of the sample (See micro 20,436). The addition of carbon appears to have stabilized the edge. Little or no intergranular attack has taken place.

(b)

20,436

500X

Typical micro showing matrix consisting of salt-and-pepper inclusions. Grains are elongated in the direction of fabrication.

Sample (2)

V-10 Ti-3 Ta

(a)

Micro 20,437

250X

Very large equiaxed grains which are larger than that of sample 9. This micro shows the edge of the affected area.

(b)

Micro 20,438

500X

Typical photomicrograph showing matrix of the above sample at 500X, Bright Field.

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Sample (3) V-2.5 Ti-1 Si

Micro 20,439

250X, B. F.

No "Edge" effect except for slight cracking. Large recrystallized grains. Some grains preferentially stained. This sample was separated at the center by crack or void. Probably caused by an imperfection in the metal during fabrication.

Sample (4) V-10 Ti-1 Nb

26

(a)

Micro 20,440 ~200X, B. F.

Extensive cracking (or intergranular corrosion) emanating from edge of sample. Evidences of grain inundation. Clusters of small grains near edge (top left). A wide stained band seems to penetrate to the base of the cracks.

(b)

Micro 20,441 500X, B. F.

Typical photomicrograph showing the matrix structure of sample (4).

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Sample (5)

V-10 Ti-1 Si

(a)

Micro 20,442

250X

(b)

20,459

1000X, B. F.

Small edge effects observed in this sample. Wide, dark band near edge. Cracking or fissures tend to follow grain boundaries. Edge effect does not follow grain boundaries. Micro 20,459 shows structure adjacent to edge.

Sample (6) V-10 Ti-3 Nb

(a)

Micro 20,539

250X, B. F.

This sample differed as compared to samples (1), (2), (3), (4), and (5) in that the edge effect was on only one side and it was darkly stained.

(b)

Micro 20,443

500X, B. F.

Slight oblique illumination. Micro shows major change in matrix grain structure, taken on side opposite stained edge. Appears to be a lamellar structure. Medium sized grains with a salt and pepper precipitate in the background.

29

Sample (7) V-10 Ti-1 Mo

(a)

Micro 20,444

250X, B. F.

This sample was divided into two separate halves, each having a macro edge effect. This effect might have been caused by imperfections in the metal. A small portion in the center of the sample was void. This area was thus exposed to the same corrosive action as the outside surfaces.

(b)

Micro 20,445

500X, B. F.

Photomicrograph taken at 500X to show structure adjacent to "edge" effect.

Sample (8) V-10 Ti-1 Cu

30

Micro 20,458

100X, B. F.

Very thick edge effect. Edge was brittle and resulted in cracking (large crack at right on micro). Very dark finger-like band (fingers formed grain boundaries) near center of sample was not as pronounced in the other sample.

Sample (9) V-10 Ti-1 Ta

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(a)

Micro 20,446

100X, B. F.

Corroded layer was very brittle; grains were separated from the specimen by cracks located at the previous grain boundaries. Extreme right of micro shows a band of inhomogeneity which passes through the middle of sample. This band exhibited different etching properties than did the remainder of the sample.

(b)

Micro 20,447

250X, B. F.

Particle phase (possibly a corrosion product) can be seen in the grain boundaries adjacent to the "edge" effect. These seem to be more heavily concentrated near this "edge" effect.

Sample (10) V-2.5 Ti

32

(a)

Micro 20,448

250X, B. F.

No edge effect except for intergranular corrosion.

(b)

Micro 20,449

500X

Typical area of matrix.

Sample (11) V-10 Ti-0.5 Si

33

Micro 20,460

100X, B. F.

This micro shows the structure after a treatment on the 3 micron paper after electropolishing. Initial electropolish heavily stained whole sample except for a narrow band in center (edge effect penetrated to parallel lines near center of sample). Extensive cracking or intergranular attack resulted at edges. This sample was by far the thinnest sample submitted for metallographic examination.