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U-15 Wt % Mo BASE DISPERSION-TYPE FUEL ELEMENT
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ABSTRACT

Potential cladding materials for a flat-plate fuel element containing a dispersion of UC or UO_2 in U-15 wt % Mo alloy were surveyed on the bases of compatibility with the fissile compounds, matrix material, protective cover materials, and liquid sodium as well as the feasibility of fabricating fuel plates by roll cladding. Radiative-capture cross sections, thermodynamic data, eutectic and intermediate compound formation, mechanical properties, and corrosion by 1000°F sodium were reported for austenitic stainless steels, chromium, nickel, niobium, molybdenum, tantalum, vanadium, and zirconium. It was recommended that "A" nickel (molybdenum barrier), Zr-3 wt % Al, Nb-2 wt % Cr, and Fansteel 82 be selected for investigation.

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CLADDING SURVEY FOR THE ENRICO FERMI REACTOR
U-15 Wt % Mo BASE DISPERSION-TYPE FUEL ELEMENT

INTRODUCTION

The cladding for reactor core materials serves as a barrier to retain fission fragments, as a corrosion-resistant barrier, and as a heat transfer medium. A metallurgical bond between the core and the cladding is generally required because of heat transfer considerations. Roll bonding usually presents an inexpensive and easy fabrication process for producing sound metallurgically bonded plates.

One of the fuel elements being developed at ORNL under the Enrico Fermi Reactor Assistance Program is a flat-plate assembly containing highly enriched UC or UO_2 dispersed in a normal U-15 wt % Mo alloy matrix and clad with a suitable structural material. It is presently envisioned that the fuel plates would be fabricated by conventional roll-bonding procedures to the following physical dimensions.

Plate thickness	0.131 in.
Clad thickness	0.005 in.
Plate width	2.450 in.
Meat width	2.200 in.
Plate length	49.5 in.
Meat length	48.0 in.

Matching yield strengths between the core and the clad during fabrication are an important criterion for a successful roll-bonding application. Adequate strength technology on the U-15 wt % Mo alloy is not available; however, by knowing the strength characteristics of the U-10 wt % Mo alloy and from a study of the phase diagram for this system, yield strengths greater than that for stainless steels or high-strength zirconium alloys at 1800°F would not be unlikely for the U-15 wt % Mo alloy. Thus, the reference rolling temperature range was selected to be between 1600 and 2000°F.

Neutron-absorption cross section, feasibility to fabricate, compatibility with the reference cermets, protective sheathing, and 900-1100°F sodium were the criteria used to evaluate possible cladding materials.

Neutron-Absorption Cross Section

Beyond the resonance region, the total nuclear cross section decreases steadily with increasing neutron energy. This represents, in nuclear nomenclature, the fast neutron region. The absorption cross sections are usually low in this region, being less than one barn in most cases.

The bulk of the fissions in the Fermi Reactor will occur in the energy range of 10-5,000 kev. (ref 1) Table I summarizes some radiative-capture cross sections of the elements under consideration as potential cladding materials along with the fission cross section of U^{235} and the absorption cross section of U^{238} .

All of the elements listed in Table I appear to have acceptable capture cross sections with the possible exception of tantalum, whose capture cross section is greater than that for U^{238} . However, the cladding thickness in the proposed fuel element is extremely thin, and the application of tantalum-bearing alloys may be feasible. Atomic Power Development Associates is investigating this possibility.²

Thermodynamic Stability

The compatibility of the reference matrix (UC or UO_2 in U-15 wt % Mo alloy) with various possible cladding materials was evaluated from thermodynamic data. Calculations based on data tabulated in Table II indicate that the only systems that are thermodynamically unstable in the reference fabrication temperature range are UC-Ti, UC-Zr, and UO_2 -Zr. However, it has been reported that the system UC-stainless steel is unstable at 1832°F. (ref 3) Mild steel and Inconel showed some reaction with UC at 1832 and 2160°F for 24 hr, (ref 4) and extensive reaction zones were produced between uranium carbide and zirconium at both temperatures.⁵ No reaction of uranium carbide with molybdenum or tantalum was observed after 24 hr at 2160°F. (ref 5)

Eutectic and Compound Formation

A diffusion bond is usually formed when two metals are rolled together at high temperatures. Across this bond, all compositions of the binary alloys will exist. Thus, intermetallic compounds will form in the bonded area when the binary system contains intermetallic compounds. Since these compounds are usually hard and brittle, the quality of the resulting bond

TABLE I. Radiative-Capture Cross Section^a

Element	Energy (kev)				
	29	63	167	500	1000
Cr	12 mb	5 mb	3.2 mb	7 mb	177 mb
Fe	15	7	4.6	5	5
Mo	179	84	-	-	-
Nb	278	142	63	60	35
Ni	32	8	-	-	-
Ta	860	510	290	230	170
U ²³⁵	3,510	2,540	-	-	-
U ²³⁵ ^b	10,210	10,570	-	-	-
U ²³⁸	483	286	-	-	-
V	27	-	-	-	-
Zr	15	11	6	-	-

^aJ. H. Gibbons, Oak Ridge National Laboratory, private communication, December 18, 1959

^bFission cross section

TABLE II. - ΔF of Formation^a for Various Oxides and Carbides^{b,c,d,e,f,g}

[illegible]

TABLE II (Continued)

Element	Oxide	Carbide	298°K 25°C	300°K 27°C	500°K 227°C	773°K 500°C	800°K 527°C	1000°K 727°C	1273°K 1000°C	1300°K 1027°C	1500°K 1227°C	Melting Point (°K)
U	UO ₂		128.5	123.0	119.1	112.5	113.0	109.0	106.5	-	99.0	3140
		UC	41	-	-	-	-	-	-	-	26.1	2550
		UC ₂	19	-	-	-	-	-	-	-	-	2700
		U ₂ C ₃	25	-	-	-	-	-	-	-	-	2700
V	V ₂ O ₃		98	-	-	90.7	-	-	82.3	-	-	22250
	V ₂ O ₅		-	-	-	-	-	-	-	49.6	-	943
		VC	27.5	-	-	-	-	-	-	-	-	3100
Zr	ZrO ₂		123	124.0	119.2	113.5	112.5	108.0	104	101.4	97.0	2950
		ZrC	35.5	-	-	-	-	-	-	-	42.2	3805

^aKcal/gram-atom of nonmetal.

^bB. S. Old, (AEC), J. Metallurgy and Ceramics, Issue No. 3, TID-67 (May, 1949).

^cA. Glossner, The Thermochemical Properties of the Oxides, Fluorides, and Chlorides to 2500°K, ANL-5750 (1957).

^dLiquid Metal Fuel Reactor; Technical Feasibility Report, BAW-2(del.) (February 21, 1957).

^eI. E. Campbell (ed.), High Temperature Technology, pp. 34, 35, 122, and 123 (1956).

^fL. L. Quill (ed.), Chemistry and Metallurgy of Miscellaneous Materials: Thermodynamics (1950).

^gAdvance Papers of an International Symposium on High Temperature Technology at Asilomar Conference Grounds, California, October 6-9, 1959, AECU-4480 (October, 1959).

^hMaterial decomposes.

could be seriously impaired. A system containing a eutectic or a minimum near the fabrication temperature could also be troublesome and should be avoided if possible. The possibility of eutectic and/or compound formation must be considered not only between the fuel matrix and cladding but also between the cladding and any secondary sheathing material. Eutectic and binary compound formation data are tabulated in Tables III through X for potential cladding and encasement elements. Binary systems containing eutectics below 2000°F of the material combinations under consideration are as follows:⁶

<u>System</u>	<u>Eutectic Temperature (°F)</u>
U-Cr	1578
U-Fe	1337, 1976
U-Ni	1364
U-V	1904
Zr-Cu	1625, 1634, 1702, 1769, 1823
Zr-Fe	1713
Zr-Ni	1762, 1805
Cu-Cr	1963
Cu-Fe	1981
Ti-Fe	1985

Mechanical Properties

Matching yield strengths, between the core and cladding at the fabrication temperature, is an important criterion for a successful roll-bonding application. Adequate strength technology on the U-15 wt % Mo alloy is not available; however, the tensile properties of arc-melted U-10 wt % Mo alloy that has been hot extruded, cold swaged, and heat treated are shown in Table XI. The reference cores, when fabricated with a dispersed phase by powder metallurgy, should have considerably higher strength. The possibility exists that materials like "A" nickel, Nichrome V, stainless steels, and high-strength zirconium alloys may have much lower yield strengths than the reference cores at the selected fabrication temperatures. This differential, could cause the cladding to rupture during rolling by the phenomenon known as "dog boning." Although it would be preferable to avoid such a condition, a possible alternative would be to have a tapered core end when cladding with the above materials.

TABLE III. Eutectic and Compound Formation of Various Elements with Cr^{a, b}

Elements	Eutectics			Intermetallic Compounds	
	Found	Wt % Cr	(°F)	Found	Symbol
C	Yes	95	2728	Yes	Cr ₃ C ₂
C	-	-	-	Yes	Cr ₇ C ₃
C	-	-	-	Yes	Cr ₂₃ C ₆
Cu	Yes	2	1963	No	-
Fe	No	-	2744 ^c	Yes	-
Mo	No	-	3092 ^c	No	-
Nb	Yes	42	2912	Yes	Cr ₂ Nb
Nb	Yes	66	3020	-	-
Ni	Yes	51	2453	No	-
Si	Yes	25	2408	Yes	CrSi
Si	Yes	57	2624	Yes	CrSi ₂
Si	Yes	72	2552	Yes	Cr ₂ Si
Si	Yes	88	2759	Yes	Cr ₃ Si
Si	-	-	-	Yes	Cr ₃ Si ₂
Ta	Yes	66	3092	Yes	Cr ₂ Ta
Ti	No	-	2534 ^c	Yes	Cr ₂ Ti
U	Yes	95	1578	No	-
V	No	-	-	No	-
Zr	Yes	30	2966	Yes	Cr ₂ Zr
Zr	Yes	82	2372	-	-

^aM. Hansen, Constitution of Binary Alloys (1958).

^bR. T. Begley, Development of Niobium Base Alloys, Westinghouse Electric Corporation (Aviation Gas Turbine Division) Report No. A-2461Z (January 15, 1958).

^cMinimum melting temperature.

TABLE IV. Eutectic and Compound Formation of Various Elements with Fe^a

Element	Eutectics			Intermediate Compounds	
	Found	Wt % Fe	(°F)	Found	Symbol
C	Yes	95.7	2096	Yes	Fe ₃ C
Cr	No	-	2744 ^b	Yes	-
Cu	No	-	1981 ^b	No	-
Mo	No	-	-	Yes	-
Nb	Yes	33	2840	Yes	Fe ₂ Nb
Nb	Yes	82	2480	-	-
Ni	No	-	2588 ^b	Yes	FeNi ₃
Si	Yes	42	2206	Yes	FeSi
Si	Yes	49.5	2214	Yes	FeSi ₂
Si	Yes	80.5	2192	Yes	Fe ₃ Si
Si	-	-	-	Yes	Fe ₅ Si ₃
Ta	Yes	20	3000	Yes	Fe ₂ Ta
Ta	Yes	80	2570	-	-
Ti	Yes	32	1985	Yes	FeTi
Ti	Yes	85	2444	Yes	Fe ₂ Ti
U	Yes	11	1337	Yes	Fe ₂ U
U	Yes	44	1976	Yes	Fe ₆ U
V	No	-	2674 ^b	Yes	FeV
Zr	Yes	16	2426	Yes	Fe ₂ Zr
Zr	Yes	84	1713	-	-

^aM. Hansen, Constitution of Binary Alloys. (1958).^bMinimum melting temperature.

TABLE V. Eutectic and Compound Formation of Various Elements with Mo^a

Element	Eutectics			Intermediate Compounds	
	Found	Wt % Mo	(°F)	Found	Symbol
C	Yes	77.5	4352	Yes	MoC
C	Yes	98.2	3992	Yes	Mo ₂ C
Cr	No	-	3092 ^b	No	-
Cu	Probable	-	-	No	-
Fe	No	-	-	Yes	-
Nb	No	-	-	No	-
Ni	Yes	53	2399	Yes	MoNi
Ni	-	-	-	Yes	MoNi ₃
Si	Yes	13	2570	Yes	MoSi ₂
Si	Yes	73	3450	Yes	Mo ₃ Si
Si	Yes	94	3758	Yes	Mo ₃ Si ₂
Ta	No	-	4712 ^b	No	-
Ti	No	-	3020 ^b	No	-
U	No	-	2070 ^b	-	-
V	No	-	-	No	-
Zr	Yes	69	2768	Yes	Mo ₂ Zr

^aM. Hansen, Constitution of Binary Alloys, (1958).

^bMinimum melting temperature.

TABLE VI. Eutectic and Compound Formation of Various Elements with Nb^{a,b,c}

Element	Eutectics			Intermediate Compounds	
	Found	Wt % Nb	(°F)	Found	Symbol
C	?	-	-	Yes	NbC
C	-	-	-	Yes	Nb ₂ C
Cr	Yes	34	3020	Yes	NbCr ₂
Cr	Yes	58	2912	-	-
Cu	Yes	-	-	Yes	-
Fe	Yes	18	2480	Yes	NbFe ₂
Fe	Yes	67	2840	-	-
Mo	No	-	-	No	-
Ni	Yes	24	2318	Yes	NbNi ₃
Ni	Yes	52	2147	-	-
Si	Yes	20	2370	Yes	NbSi ₂
Si	Yes	42	3362	Yes	Nb ₄ Si
Si	Yes	91	3416	Yes	Nb ₅ Si ₃
Ta	No	-	-	No	-
Ti	No	-	3128 ^d	No	-
U	Probable	-	2070	No	-
V	No	-	3290 ^d	No	-
Zr	No	-	3164 ^d	No	-

^aM. Hansen, Constitution of Binary Alloys. (1958).

^bR. T. Begley, Development of Niobium Base Alloys, Westinghouse Electric Corporation (Aviation Gas Turbine Division) Report No. A-24612 (January 15, 1958).

^cJ. E. McCauley, WAPD-TM-195, December, 1959 (classified).

^dMinimum melting temperature.

TABLE VII. Eutectic and Compound Formation of Various Elements with Ni^a

Element	Eutectics			Intermediate Compounds	
	Found	Wt % Ni	(°F)	Found	Symbol
C	Yes	98	2395	Yes	Ni ₃ C
Cr	Yes	49	2453	No	-
Cu	No	-	1981 ^b	No	-
Fe	No	68	2588 ^b	Yes	Ni ₃ Fe
Mo	Yes	47	2399	Yes	NiMo
Mo	-	-	-	Yes	Ni ₃ Mo
Nb	Yes	48	2147	Yes	Ni ₃ Nb
Nb	Yes	76	2318	-	-
Si	Yes	62	1770	Yes	NiSi
Si	Yes	71	1767	Yes	NiSi ₂
Si	Yes	82.5	2309	Yes	Ni ₂ Si
Si	Yes	88.5	2052	Yes	Ni ₃ Si
Si	-	-	-	Yes	Ni ₃ Si ₂
Ta	Yes	62	2489	Yes	NiT ₃
Ta	Yes	-	-	Yes	Ni ₂ Ta ₃
Ta	-	-	-	Yes	Ni ₃ Ta
Ti	Yes	28.5	1751	Yes	NiT ₃
Ti	Yes	65	2030	Yes	NiT ₂
Ti	Yes	83.8	2348	Yes	Ni ₃ Ti
U	Yes	10.5	1364	Yes	NiU ₆
U	Yes	71	2030	Yes	Ni ₂ U
U	-	-	-	Yes	Ni ₅ U
V	Yes	52.5	2197	Yes	Ni ₂ V
V	-	-	-	Yes	Ni ₃ V
Zr	Yes	17	1761	Yes	NiZr
Zr	Yes	27	1805	Yes	NiZr ₂

^aM. Hansen, Constitution of Binary Alloys (1958).^bMinimum melting temperature.

TABLE VIII. Eutectic and Compound Formation of Various Element with Ta^a

Element	Eutectics			Intermediate Compounds	
	Found	Wt % Ta	(°F)	Found	Symbol
C	Yes	90	5972	Yes	TaC
C	Yes	99.4	5072	Yes	Ta ₂ C
Cr	Yes	34	3092	Yes	TaCr ₂
Cu	Immiscible	-	-	No	-
Fe	Yes	20	2570	Yes	TaFe ₂
-	Yes	80	3000	-	-
Mo	No	-	4712 ^b	No	-
Nb	No	-	-	No	-
Ni	Yes	40	2552	Yes	TaNi ₂
Ni	Yes	64	2480	Yes	TaNi ₃
Si	Yes	6	2525	Yes	TaSi ₂
Si	Yes	82	3794	Yes	Ta ₂ Si
Si	Yes	94	4350	Yes	Ta ₄ Si
Si	Yes	> 95	4190	Yes	Ta ₅ Si ₃
Ti	No	-	3056 ^b	No	-
U	No	-	2057 ^b	No	-
V	No	-	-	Yes	-
Zr	Yes	80	3362	-	-

^aM. Hansen, Constitution of Binary Alloys (1958).

^bMinimum melting temperature.

TABLE IX. Eutectic and Compound Formation of Various Elements with V^a

Element	Eutectics			Intermediate M. Compounds	
	Found	Wt % V	(°F)	Found	Symbol
C	Yes	96.5	3002	Yes	VC
C	-	-	-	Yes	V ₂ C
Cr	No	-	-	No	-
Cu	-	-	-	-	-
Fe	No	-	2674 ^b	Yes	VFe
Mo	No	-	-	No	-
Nb	No	-	3290 ^b	No	-
Ni	Yes	52.5	2197	Yes	VNi ₂
Ni	-	-	-	Yes	VNi ₃
Ni	-	-	-	Yes	V ₃ Ni
Si	Yes	5	2525	Yes	VSi ₂
Si	Yes	60	3056	Yes	V ₃ Si ₇
Si	Yes	92.5	3344	Yes	V ₅ Si ₃
Ta	No	-	-	Yes	9
Ti	No	-	2948 ^b	No	-
U	Yes	4.5	1904	No	-
Zr	Yes	70	2246	Yes	V ₂ Zr

^aM. Hansen, Constitution of Binary Alloys (1958).

^bMinimum melting temperature.

TABLE X. Eutectic and Compound Formation of Various Elements with Zr^{a, b}

Elements	Eutectics			Intermediate Compounds	
	Found	Wt % Zr	(°F)	Found	Symbol
C	Yes	-	4406	Yes	ZrC
Cr	Yes	18	2372	Yes	ZrCr ₂
Cr	Yes	70	2966	-	-
Cu	Yes	10	1769	Yes	ZrCu
Cu	Yes	46	1625	Yes	ZrCu ₃
Cu	Yes	53	1634	Yes	Zr ₂ Cu
Cu	Yes	62	1702	Yes	Zr ₂ Cu ₃
Cu	Yes	79	1823	Yes	Zr ₂ Cu ₅
Fe	Yes	16	1713	Yes	ZrFe ₂
Fe	Yes	84	2426	-	-
Mo	Yes	32	2768	Yes	ZrMo ₂
Nb	No	-	3164 ^c	No	-
Ni	Yes	16	2534	Yes	ZrNi
Ni	Yes	59	2570	Yes	ZrNi ₃
Ni	Yes	73	1805	Yes	ZrNi ₄
Ni	Yes	83	1762	Yes	Zr ₂ Ni
Si	Yes	25	2480	Yes	ZrSi
Si	Yes	97.1	2930	Yes	Zr ₂ Si
Si	-	-	-	Yes	Zr ₄ Si
Si	-	-	-	Yes	Zr ₄ Si ₃
Si	-	-	-	Yes	Zr ₅ Si ₃
Si	-	-	-	Yes	Zr ₆ Si ₅
Ta	Yes	20	3362	-	-
Ti	No	-	2921 ^c	No	-
U	No	-	2071 ^c	Yes	Zr ₃ U
V	Yes	30	2246	Yes	ZrV ₂

^aM. Hansen, Constitution of Binary Alloys (1958).

^bW. E. McCauley, WAPD-TM-195, December, 1959 (classified).

^cMinimum melting temperature.

TABLE XI. Tensile Properties of U-10 % Mo Alloy^a

Test Temperature (°F)	Ultimate Tensile Strength 1000 psi	Yield Strength 1000psi	Tensile Elongation (%)
75	140	140	8.5
250	105	101	11.8
500	92	85	10.8
750 ^b	82	79	4.0
1000	52	44	38.0
1250	13	9	161.0

^a Enrico Fermi Atomic Power Plant, APDA-124, p. 230 (January, 1959).

^b Material probably transformed during test.

Tensile strength, creep, and/or creep-rupture properties are tabulated in Tables XII through XXX for some of the potential cladding materials. Tantalum-, vanadium-, molybdenum-, niobium-, and chromium-base alloys have desirable high-temperature strength properties. However, nearly all are considerably affected by small amounts of oxygen and/or nitrogen. Two new alloys, Nb-1-2 wt % Cr and Nb-3-4 wt % Zr, are under investigation at Battelle Memorial Institute for EBR-2 cladding application for Argonne National Laboratory.⁷ Both of these alloys have a yield strength of approx 69,000 psi at 1472°F, (ref 8) and it is expected that their yield strengths will match those of the reference cores in the reference fabrication temperature range.

Fabrication and Protective Sheathing

One of the most important limitations to cladding the reference cores with stainless steels and/or nickel-base alloys is the minimum solidus temperatures in the systems between uranium and chromium, iron, or nickel. To avoid this hazardous condition, a mutually compatible barrier material should be interposed between the core and the clad. Molybdenum appears to be an excellent barrier material when cladding the reference cores with nickel.⁹

It appears that stainless steels will not adequately bond to molybdenum when rolled in the reference temperature range.¹⁰ However, by plating the stainless steel with nickel, satisfactory bonding may be feasible.

Stainless steels, nickel-, and zirconium-base alloys can be fabricated by nearly all standard commercial techniques in the reference temperature range. Protective sheathing would not be required during the hot working of stainless steels and most nickel-base alloys. However, zirconium alloys for this application should be protected from contamination or reactions with air. Ti-Namel (titanium-killed steel) is normally used as the sheathing material for zirconium alloys at temperatures up to 1650°F. Above 1650°F, sheathing difficulties may be prevalent due to the multitude of eutectics and bonding characteristics of zirconium with Ti-Namel and most protective materials.

Heating tantalum and niobium in air and working at the reference temperature range is not feasible and these metals must be sheathed to prevent contamination that would cause embrittlement. Austenitic stainless

TABLE XII. Tensile Properties of 18/8 Stainless Steel^{a,b,c,d}

Materials (Wrought Steels)	Test Temperature (°F)	Ultimate Tensile Strength 1000 psi	Yield Strength 1000 psi	Elongation (%)
18/8	68	75.8	30.4	63
	1095	43.8	11.6	40
	1500	18.8	9.0	39
18/8/1 Ti	68	75.8	29.4	58
	1095	43.8	17.0	43
	1500	19.6	11.6	73
18/8/1 Nb	68	81.2	35.2	50
	1095	50.0	25.4	39
	1500	20.6	17.4	76
Type 347	R.T.	80.0	30.0	40
	1200	51.2	41.0	46
	1470	23.0	14.0	75
Type 309	R.T.	84	57	55
	1200	52	31	38
	1600	22	20	51

^aG. H. Boss, High Temperature Mechanical Properties of Metals and Alloys, ORNL-CF 57-11-72, (November 8, 1957).

^bF. H. Keating, Chromium-Nickel Austenitic Steels (1956).

^cAllegheny Ludlum Steel Corporation, Stainless Steel Handbook, 1956.

^dB. Kopelman, Materials for Nuclear Reactors (1959).

TABLE XIII. Creep Strength of 18/8 Stainless Steel^a

Material	Test Temperature (°F)	Stress to Cause 1% Elongation in 10,000 hr
18/8	895	21,400
	1000	15,600
	1200	6,200
18/8/1 Ti	895	22,200
	1000	16,200
	1200	7,200
18/8/1 Nb	895	-
	1000	17,400
	1200	7,400

^aF. H. Keating, Chromium-Nickel Austenitic Steels (1956).

TABLE XIV. Tensile Properties of Cr^a

Test Temperature (°F)	Ultimate Tensile Strength 1000 psi	Yield Strength 1000 psi	Elongation (%)
1000	78	56	25
1400	52	44	44
1600	37	32	43
1800	23	18	20

^aF. R. Schwartzberg, H. R. Ogden, and R. I. Jaffee, Ductile-Brittle Transition in the Refractory Metals, DMIC Report 114 (June 25, 1959).

TABLE XV. Rupture Strength of Cr Alloys^a

Materials (Wt %)	Test Temperature (°F)	Stress 1000 psi	Rupture (hr)
Cr-1 to 3% Nb (extruded)	1800	15	225
Cr-1 to 3% Ta (extruded)	1800	15	30
Cr-1 to 3% Ti (extruded)	1800	15	20
Cr-2% Nb (extruded)	2000	20	20

^aD. J. Maykuth, The Status of Chromium-Base Alloy Development, DMIC Memorandum 6 (January 30, 1959).

TABLE XVI. Tensile Properties of Mo^a

Material	Test Temperature (°F)	Ultimate Strength 1000 psi	Yield Strength 1000 psi	Elongation (%)	Rupture (%)
Recrystallized Mo	85	81.2	65.2	29	21.5
0.003 wt % O ₂	220	66.2	47.0	50	64.5
0.003 wt % H ₂	437	53.5	30.2	50	71.5
0.001 wt % N ₂	610	46.0	28.1	46	-
0.05 wt % C	850	43.0	26.0	48	81.5
Arc melted	1021	42.6	24.2	49	92.0
	1279	39.0	20.0	43	96.0
	1448	38.5	19.0	38	95.5
	1645	35.5	18.5	38	95.5
	1790	34.5	18.0	41	97.5
	2020	24.9	16.0	72	97

^aR. W. Douglass, Physical and Mechanical Properties of Molybdenum and the Mo-0.5 Ti Alloys, DMIC Memorandum 14 (April 10, 1959).

TABLE XVII. Tensile Properties of Mo and Mo Alloy^a

Materials (wt %)	Test Temperature (°F)	Ultimate Tensile Strength 1000 psi	Yield Strength ^b 1000 psi	Elongation (%)	Rupture (%)
5/8-in. Mo rod, as rolled	81	102.2	78.8	40	61.1
	750	79.3	53.4	20	82.4
	1200	69.6	49.8	18	84.2
	1600	52.0	37.0	24	88.6
5/8-in. Mo rod, stress relieved 1 hr at 1800°F	81	97.2	82.9	42	69.0
	750	62.4	57.2	20	81.2
	1200	65.2	48.1	22	86.1
	1600	52.4	33.4	24	88.6
5/8-in. Mo-0.5-in. Ti rod, as rolled	82	112.9	96.7	29	59.7
	750	100.4	78.9	18	76.1
	1200	101.3	80.6	18	82.6
	1600	86.9	81.0	17	84.0
5/8-in. Mo-0.5-in. Ti rod, stress relieved 1 hr at 1800°F	82	132.1	99.1	31	70.0
	750	110.0	89.0	18	72.8
	1200	100.5	84.0	17	74.1
	1600	88.3	76.5	15	71.1

^aR. W. Douglass, Physical and Mechanical Properties of Molybdenum and the Mo-0.5 Ti Alloy, DMIC Memorandum 14 (April 10, 1959).

^b0.1% offset.

TABLE XVIII. Creep Rupture Data of Mo^a

Materials (wt %)	Test Temperature (°F)	Stress 1000 psi	Rupture (hr)	Elongation (%)	Rupture (%)	Creep Rate (%/hr)
Unalloyed Mo (stress relieved)	1600	45.0	0.3	17.4	92.0	-
		37.5	8.0	17.8	92.9	1.7
		30.0	206.3	18.0	93.4	0.012
Unalloyed Mo (recrystallized)	1600	22.3	2.0	54.9	94.0	12.2
		22.0	2.2	64.2	93.1	10.5
		17.5	19.7	40.7	86.5	0.95
		14.0	353.5 ^b	34.2	-	0.067
Mo-0.5 Ti alloy (stress relieved)	1000	75.0	260.4 ^b	0.5	-	N11
	1200	78.5	255.4 ^b	1.3	-	0.0016
	1400	70.0	254.7 ^b	15.2	72.1	0.011
	1600	65.0	171.0	17.5	77.5	0.03
Mo-0.5 Ti alloy (recrystallized)	1000	38.0	256.1 ^b	8.5	-	N11
	1200	38.0	216.4 ^b	8.6	-	0.0004
	1400	35.0	402.5 ^b	15.9	-	0.017
	1600	33.5	379.4 ^b	15.3	-	0.027
	1600	35.0	74.9	32.8	86.4	0.19

^aR. W. Douglass, Physical and Mechanical Properties of Molybdenum and the Mo-0.5 Ti Alloy, DMIC Memorandum 14 (April 10, 1959).

^bTest discontinued.

TABLE XIX. Tensile Properties of Nb and Nb Alloys^{a,b,c,d,e}

Materials (wt %)	Test Temperature (°F)	Ultimate Tensile Strength 1000 psi	Yield Strength 1000 psi	Elongation (%)	Rupture (%)
Arc-cast Nb	R.T.	48.4	36.0	48.0	63.5
	1200	22.1	10.0	43.0	72.0
	1600	15.2	9.4	47.0	96.0
	2000	10.1	8.1	34.0	~ 100
	2400	5.5	4.0	70.0	81.8
Nb-5 V	80	86.0	74.0	27	72
	2000	37.0	34.0	37	-
Nb-7.3 V	70	87.0	78.5	24	-
	600	81.4	57.3	23	-
	1200	76.9	48.8	18	-
Nb-1 W	80	48.0	44.0	-	-
	2000	12.0	11.0	-	-
Nb-5 W	80	-	44.0	-	-
	2000	14.0	12.0	-	-
Nb-1.84 Cr	1200	115.0	107.0	4 ^f	5
	1470	81.6	68.7	14 ^f	37
Nb-4.33 Zr	1200	82.4	-	4 ^f	7
	1470	76.4	69.0	4 ^f	3
Nb-10 Zr	80	82.6	61.4	6.5	-
Nb-7.4 Mo	70	76.6	62.2	20	-
	600	67.2	46.2	14	-
	1200	44.1	35.7	3	-
Fansteel 82 (Nb-33 Ta-0.7 Zr)	1600	-	40	4	-
	2000	30	27	-	-
	2000 ^g	45	40	8	-
	2400	12	-	-	-

^aR. W. Dayton and C. R. Tipton, EMI-1391, p. 33 (November, 1, 1959)(classified).^bR. B. Norclen (ed.), Chemical Engineering 66, 208 (June 15, 1959).^cR. T. Begley, Development of Niobium-Base Alloys, Westinghouse Electric Corporation (Aviation Gas Turbine Division), Report No. A-2551Z (November 15, 1958).^dP. R. Schwartzberg, and W. D. Klopp, Elevated Temperature Mechanical Properties and Oxidation Resistance of Columbium and Its Alloys, DMIC Memo No. 8 (February 4, 1959).^eKAPL-1850-11, p. V.36 (classified).^fElongation in 1 in. ^gTest performed in an argon atmosphere.

TABLE XX. Minimum Creep Rates for Nb and Nb Alloys^{a, b}

Materials (wt %)	Test Temperature (°F)	Stress 1000 psi	Minimum Creep Rate 0.0001 %/hr	Duration (hr)
99.92 Nb (production Nb)	752	8	0.44	1819
	752	16	0.87	1536
	932	16	0.24	1870
	932	20	5.3	338
	1112	8	1.6	1325
	1112	16	0.2	2117
Nb-7.3 V	1200	20	nil	-
	1200	30	0.5	-
	1200	30	nil	-
	1382	40	16	-
Nb-7.4 Mo	1200	20	nil	-
	1200	30	1.2	-
	1382	30	660	-

^aT. J. Heal, The Mechanical and Physical Properties of Magnesium and Niobium Canning Materials, A/Conf. 15/p/305 (June 3, 1958).

^bKAPL-1850-12, p. V. 50 (classified).

TABLE XXI.. Creep-Rupture Data for Nb and Nb Alloys^{a, b}

Materials (wt %)	Test Temperature (°F)	Stress 1000 psi	Rupture (hr)	Elongation (%)
High-purity, vacuum-sintered Nb	1800	28	358	9.9
	1800	35	75	6.4
	2000	20	87	8.6
	2000	25	12	15.6
Nb-7.3 V	1200	20	> 500	n11
	1200	30	> 100	n11
	1382	40	> 307	> 1.0
Nb-7.4 Mo	1200	20	> 500	-
	1200	30	> 432	> 0.4
	1382	30	> 177	23.2

^aKAPL-1850-12, p. V. 50 (classified).

^bR. T. Begley, Development of Niobium Base Alloys, Westinghouse Electric Corporation (Aviation Gas Turbine Division) Report No. A-2293 (January, 1957).

TABLE XXII. Tensile Properties of Ni Alloys^a

Materials	Test Temperature (°F)	Ultimate Tensile Strength 1000 psi	Yield Strength 1000 psi	Elongation (%)
Ni "A"	R.T.	63.0	21.0	51.0
	1000	31.5	13.5	69.0
	1400	14.0	7.5	89.0
Nichrome V	R.T.	121.0	59.0	44.5
	1110	77.7	38.8	26.0
	1470	25.1	18.4	35.0
	1830	8.1	5.1	30.0
Inconel	R.T.	90.5	36.5	47.0
	2000	84.0	28.5	47.0
	1400	27.5	17.0	46.0
	1800	7.5	4.0	118.0

^aG. H. Boss, High-Temperature Mechanical Properties of Metals and Alloys, ORNL CF-51-11-72.

TABLE XXIII. Creep Strength of Ni Alloys^a

Materials	Test Temperature (°F)	Stress to cause 1% elongation in 10,000 hr
Ni "A"	900	3,600
	1000	3,100
	1100	2,600
	1200	2,400
Inconel	1000	25,000
	1100	12,000
	1200	9,300

^aG. H. Boss, High Temperature Mechanical Properties of Metals and Alloys, ORNL CF 51-11-72.

TABLE XXIV. Tensile Properties of Annealed Ta Sheet^a

Materials	Test Temperature (°F)	Ultimate Tensile Strength 1000 psi	Yield Strength 1000 psi	Elongation (%)
Recrystallized sheet	R.T.	67.1	57.3	25.3
Recrystallized rod (annealed 1 hr at 1700°C)	R.T.	49.8	39.3	45
Annealed sheet	R.T.	40-50	30-40	30-40
Cold-worked sheet	R.T.	100-200	95-105	2.5
Annealed high purity sheet (1 hr at 1200°C)	R.T.	29.1	14.6	51
Annealed sheet	1000	59.9	26.1	16.2
	1205	44.7	18.9	17.3
	1400	30.3	16.9	23.1
	1595	22.2	12.1	32.8
	1800	21.6	12.4	33.1
	2000	16.8	8.1	43.2

^aH. R. Ogden, Physical and Mechanical Properties of Tantalum, DMIC Memorandum 32 (August 28, 1959).

TABLE XXV. Minimum Creep Rates for Ta^a

Materials	Test Temperature (°F)	Stress 1000 psi	Minimum Creep rate 0.0001 %/hr
Arc-cast Ta	900	25	nil
	900	40	4.8
	1200	12.5	nil
	1200	17.5	2.1
	1500	8	nil
	1500	10	0.3
Rolled and annealed sintered sheet (annealed between 2600-2800°F)	1200	10	0.5
	1200	20	110
	1200	28	11,000

^aD. C. Drennen et al., High-Temperature Mechanical Properties of Tantalum, BMI-1326 (March 2, 1959).

TABLE XXVI. Tensile Properties of V Alloys^a

Materials (wt %)	Test Temperature (°F)	Ultimate Tensile Strength 1000 psi	Yield Strength 1000 psi	Elongation (%)
V; annealed at 1000°C (1355 grains/mm ²)	80	60.6	53.7	14.2
	800	66.3	35.0	12.6
	1520	12.2	9.4	17.9
	1880	7.7	4.8	37.2
V-20 Ti	930	100	-	-
	1290	85	-	-
	1650	52	-	-
V-20 Ti-5 Cr	930	108	-	-
	1290	93	-	-
	1650	57	-	-
V-50 Ti-5 Al	930	110	-	15.6
	1290	85	-	12.5
	1650	27	-	-

^aW. Rostoker, The Metallurgy of Vanadium (1958).

TABLE XXVII. Creep Rates for V^a

Material	Test Temperature (°F)	Stress 1000 psi	Creep rate 0.0001 %/hr	Duration (hr)
V; as swaged	932	12	1.4	2781
and heat treated	1112	8	0.30	2797
1/2 hr at 1100°C	1112	8	0.18	3037

^aW. Rostoker, The Metallurgy of Vanadium (1958).

TABLE XXVIII. Creep-Rupture Properties of V Alloys^a

Materials (wt %)	100 hr Stress Rupture	
	Test Temperature (°F)	Stress, 1000 psi
V-50 Ti-5 Al	930	95
	1110	37
V-50 Ti-5 Cr	930	60
	1110	24
V-40 Ti-5 Al	930	100
	1110	45

^aW. Rostoker, The Metallurgy of Vanadium (1958).

TABLE XXIX. Tensile Properties of Zr Alloys^{a, b}

Materials (wt %)	Test Temperature (°F)	Ultimate Tensile Strength 1000 psi	Yield Strength 1000 psi	Elongation (%)
Zr + 2 Al	R.T.	107.2	90.2	13.5
	1050	59.1	42.9	24.3
	1200	45.3	31.2	43
	1472	15.8	13.2	-
Zr + 3 Al	R.T.	129.4	115.8	11.5
	1050	73.3	49.1	23
	1200	57.9	36.5	32.5
	1472	25.1	19.6	55
Zr + 1.5 Al + 3 Sn	R.T.	114.5	103.0	13
	1050	60.8	42.0	25.5
	1200	48.2	34.0	32.0
	1472	23.5	21.6	188
Zr + 1.5 Al + 1.5 Sn + 1.5 Mo	R.T.	127.3	118.0	10.0
	1050	63.5	45.9	31
	1200	44.7	30.6	41.7
Zr + 3 Al + 3 Sn	R.T.	136.8	122.3	3.0
	1050	78.7	52.1	17.5
	1200	67.1	39.0	15.0

^aR. K. Wagner and H. E. Kline, High-Strength Zirconium Alloys, Atomics International, NAA-SR-3481 (July 15, 1959).

^bA. L. Lotts (ed.), MTM-12 (March 25, 1959)(classified).

TABLE XXX. Minimum Creep Rates for Zirconium Alloys at 1050°F.^a

Materials (wt %)	Stress 1000 psi	Minimum Creep Rate 0.0001 %/hr
Zr + 1.5 Al	25	200
	25	150
Zr + 1.5 Al + 1.5 Sn	25	15
Zr + 1.5 Al + 3 Sn	25	23
Zr + 1.5 Al + 1.5 Mo	25	13
Zr + 1.5 Al + 1.5 Sn + 1.5 Mo	7.2	0.5
	12.5	1.8
	17.5	3.8
	25	13
	25	17
Zr + 2 Al	25	60
Zr + 3 Al	25	65
	25	16
Zr + 3 Al + 1.5 Sn	25	25
	25	21
Zr + 3 Al + 3 Sn	25	32
	25	27
Zr + 3 Al + 1.5 Sn + 1.5 Mo	12.5	2.1
	25	7
	35	50

^aR. K. Wagner and H. E. Kline, High-Strength Zirconium Alloys, Atomic International NAA-SR-3481 (July 15, 1959).

steels should be satisfactory sheath materials for hot-working vanadium alloys in the temperature range of 1500-2000°F, ^(ref 11) and there is every indication that it would be compatible with tantalum and niobium in this temperature range, also.

The Nb-1-2 wt % Cr and the Nb-3-4 wt % Zr alloys are composed of a single phase which may eliminate the possibility of eutectic formations between U-Cr and Fe-Zr. ^(ref 8) The materials are easily rolled at 800°F without protective sheathing; however, at higher rolling temperatures the alloys must be protected from oxidation. ⁸

Fansteel 82, a commercial niobium-base alloy composed of Nb-33 wt % Ta-0.7 wt % Zr, appears to be the only refractory material worthy of special attention from a fabrication standpoint. This alloy has been reported to be superior to many so-called oxidation resistant niobium-base materials in high-temperature, flowing air. For example, at 2000°F for 16 hr, this new alloy shows scaling of only 4 mils; ^(ref 12) however, its utility would depend on its propensity to internal oxidation if exposed to air during fabrication. ¹³

Commercially pure chromium and molybdenum alloys are generally warm rolled in the temperature range of 2200-2400°F, which is considerably above the reference rolling temperature. Essentially no success has been achieved in fabricating chromium-rich alloys that weigh more than 50 g; however, thin molybdenum sheet has been rolled successfully at temperatures as low as 1600°F. ^(ref 14)

Corrosion in Sodium

All of the materials under consideration appear to have acceptable corrosion resistance to liquid sodium at 900-1100°F, if the oxygen content of the sodium is kept at a low value. As shown in Tables XXXI through XXXIII, under dynamic conditions, the corrosion of stainless steels, zirconium, niobium, and vanadium is essentially nonexistent. Sodium does not appear to attack molybdenum at 1800°F, and it is expected that tantalum would exhibit the same behavior. ¹⁵ Data on the corrosion of stainless steels in sodium at temperatures between 1000 and 1500°F are not available, and the possibility that appreciable mass transfer takes place within this range does exist. Appreciable mass transfer may take place in the Na-Ni system also, since the equilibrium solubility of nickel in sodium at 500

TABLE XXXI. Corrosion of Nb and V in Liquid Na Under Zr Hot-Trapped Conditions^a

Materials	Test Temperature (°F)	Velocity ft/sec	Exposure Time (hr)	Oxygen Content (ppm)	Change in Hardness (D.P.N.)	Corrosion Rate ^b (mils/year)
Nb	1112	30	162	5	- 10	0.89
Nb	932-1112	30	168	4	- 10	0.54
V	1022	25	216	5	- 25	0.24
V	1112	25	127	8	+ 15	0.23
Nb leading coupled to V	1112	25	152	4	- 35 (Nb) - 15 (V)	0.48 (Nb) 0.48 (V)
V leading coupled to Nb	1112	25	144	-	- 2 (Nb) - 2 (V)	0.60 (Nb) 0.60 (V)

^a J. W. Evans and A. Thorley, Corrosion of Niobium and Vanadium in Liquid Sodium, United Kingdom Atomic Energy Authority, IGB-TN/C-1019 (1958).

^b Converted from inches/month.

TABLE XXXII. Corrosion of Zirconium Alloys in 1000°F Sodium^a

Materials (wt %)	Oxygen Content (ppm)	Velocity	Corrosion Rate in mils/year ^b		
			75 hr	163 hr	303 hr
Zr + 2 Al	10	N.C.	1.21	0.85	0.68
Zr + 3 Al	10	N.C.	1.28	0.82	0.54
Zr + 3 Al + 1.5 Sn	10	N.C.	1.21	0.82	0.51
Zr + 3 Al + 3 Sn	10	N.C.	1.21	0.72	0.47
Zr + 3 Al + 1.5 Sn + 1.5 Mo	10	N.C.	1.63	1.01	0.63
Zr + 1.5 Al + 1.5 Sn	10	N.C.	0.99	0.78	0.63
Zr + 1.5 Al + 3 Sn	10	N.C.	1.06	0.68	0.47
Zr + 1.5 Al + 1.5 Sn + 1.5 Mo	10	N.C.	1.28	1.08	0.70

^aR. K. Wagner and H. E. Kline, High-Strength Zirconium Alloys, Atomica International, NAA-SR-3481 (July 15, 1959).

^bConverted from mg/cm².

TABLE XXXIII. Summary of High-Temperature Corrosion Properties of Austenitic Stainless Steels in Sodium

Materials	Organization	Test Method	Maximum Hot Leg Temperature (°F)	Sodium ΔT (°F)	Test Results
Type 347 stainless steel	KAPL ^a	Forced convection and thermal convection loops	950	-	Equivalent to weighting error
Type 316 stainless steel	NDA ^b	Thermal convection loop	1600	500	Thickness change of specimen in hot leg was -1.09 mils/yr. ^(d)
Types 304, 347, and 316 stainless steel	ORNL ^c	Forced convection and thermal convection loops	1500	300	No detectible cold leg deposits, intergranular attack along hot leg sections ranging from 1-1/2 to 3 mils in 1000 hr.

^aE. G. Brush and R. F. Hoenig, "Low Cost Metals for Sodium Heat Transfer Systems," Liquid Metals Technology, Part I, AIChE, p. 59 (1957).

^b"An Experimental Investigation of Mass Transfer in Sodium System at 1200°F," Proposal NDA 3-404 to U.S. AEC, Nuclear Development Corporation of America, August 4, 1958.

^cJ. H. DeVan, Oak Ridge National Laboratory, private communication, January 6, 1960.

^dConverted from mg/dm²-mo

and 1000°F can be calculated to be 8.7 and 18.6 ppm, respectively.¹⁶ However, it has been reported that nickel was not attacked by sodium in the temperature range of 752 and 1076°F under low-velocity dynamic conditions.¹⁷

EVALUATION OF MATERIALS

From an analysis of the previous sections, it is evident that utilization of a developed material for cladding the Phase II fuel element is unlikely. However, several materials possess good high-temperature strength and appear corrosion resistant in sodium. The most promising for a roll-bonding application are listed below:

1. "A" nickel (molybdenum barrier)
2. Zr-3 wt % Al
3. Nb-2 wt % Cr
4. Nb-33 wt % Ta-0.7 wt % Zr

Table XXXIV presents some of the advantages and disadvantages of the recommended cladding materials.

CONCLUSIONS

On the basis of this literature survey, the following conclusions are justified:

1. A developed material as a likely cladding for the U-15 wt % Mo matrix cermet is not available.
2. Extensive development on the four recommended cladding materials will be required before one can be selected for cladding the U-15 wt % Mo matrix cermet.

TABLE XXXIV. Advantages and Disadvantages of Recommended Cladding Materials

Cladding Materials	Advantages	Disadvantages
Fansteel 82	<ol style="list-style-type: none"> 1. Possibility of rolling in air 2. High strength, Y.S. $\approx$ 40,000 psi at 1600°F 3. Core compatibility expected 	<ol style="list-style-type: none"> 1. High fast cross section 2. High cost $\approx$ \$80/lb 3. Possible limited temperature in sodium because of internal oxidation
Nb-2% Cr	<ol style="list-style-type: none"> 1. High strength, Y.S. $\approx$ 68,700 psi at 1470°F 2. Core compatibility expected 3. Single phase alloy 	<ol style="list-style-type: none"> 1. Technology limited 2. Possible limited temperature in sodium because of internal oxidation 3. High cost $\approx$ \$60/lb
Zr-3% Al	<ol style="list-style-type: none"> 1. Less expensive than Nb-base alloys $\approx$ \$30/lb 2. Technology known 3. May have sufficient strength, Y.S. $\approx$ 20,000 psi at 1472°F 	<ol style="list-style-type: none"> 1. May not be compatible with core 2. Sheathing problems if rolled above 1650°F 3. Possible structural changes in reactor
"A" nickel (Mo barrier)	<ol style="list-style-type: none"> 1. Less expensive than Zr-base alloys $\approx$ \$2/lb 2. Sheathing may not be required during rolling 3. Technology known 	<ol style="list-style-type: none"> 1. Possible eutectic formation during rolling 2. Possible inter-metallic formation during bonding 3. May require taper end design.

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