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of

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT

WAR METALLURGY DIVISION

No. 8908

Final Report

on

HEAT RESISTING METALS FOR GAS TURBINE PARTS (N-102): CHROMIUM-BASE ALLOYS

by

ROBERT I. PARKE AND ALVIN J. HERZIG
CLIMAX MOLYBDENUM COMPANY

OSRD No. 6547

Serial No. [illegible]-55[illegible]

Copy No. 11

January 21, 1946

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Final Report

NDRC Research Project NRC-8, Contract OEMsr-457

HEAT RESISTING METALS FOR GAS TURBINE PARTS (N-102): CHROMIUM BASE ALLOYS

November 28, 1945

From: CLIMAX MOLYBDENUM COMPANY

Report Prepared by: Robert M. Parke

Technical Representative: Alvin J. Herzig

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January 21, 1946

To: Dr. James B. Conant, Chairman
National Defense Research Committee of the
Office of Scientific Research and Development

From: War Metallurgy Division (Div. 18), NDRC

Subject: Final Report on "Heat Resisting Metals for Gas Turbine Parts (N-102): Chromium-base Alloys"

The attached final report by Robert M. Parke, submitted by A. J. Herzig, Technical Representative of the Climax Molybdenum Company for NDRC Research Project NRC-8, has been approved by the representatives of the War Metallurgy Committee in charge of the work.

This report describes the development of a new class of metallic alloys, in which chromium is the alloy base.

I recommend acceptance as a satisfactory final report on the work done under Contract OEMsr-457 with the Climax Molybdenum Company.

Respectfully submitted,

Clyde Williams

Clyde Williams, Chief
War Metallurgy Division, NDRC

Enclosure

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"The U.S. Government is absolved from any litigation which may ensue from the contractor's infringing on the foreign patent rights which may be involved."

PREFACE

This report is pertinent to the problems designated by the Navy Department as N-102, and to the projects designated by the War Metallurgy Committee as NDRC Research Projects NRC-8.

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NDRC Research Project NRC-8, OEMsr-457

HEAT RESISTING METALS FOR GAS TURBINE PARTS (W-102)

March 15, 1942 to August 31, 1945

From: CLIMAX MOLYBDENUM COMPANY

Report Prepared By: ROBERT M. PARKE

ABSTRACT

This report of work under Contract OEMsr-457 at the research laboratory of Climax Molybdenum Company of Michigan describes the results of a 42-month search for heat resistant metals for gas turbine blades which ended in the development of a new series of alloys. The principal element of the series is chromium.

The chromium-rich portions of thirteen binary and nine ternary systems of chromium have been surveyed.

Methods of melting, purifying, casting, and machining the alloys have been devised.

The most promising alloys for gas turbine blades are the chromium-iron-molybdenum ternary alloys ranging in composition between 60% chromium, 15% iron, 25% molybdenum, and 60% chromium, 25% iron, 15% molybdenum. For service at 1600°F. the 60Cr-15Fe-25Mo alloy is believed to be the best of the series. This alloy, in a stress-rupture test, supported a stress of 30,000 psi at 1600°F. for 430 hours, with 6.0% elongation and 6.3% reduction of area. For service at 1350°F. the 60Cr-25Fe-15Mo alloy is considered the best of the series. This alloy supported a stress of 50,000 psi for 1414 hours at 1350°F., with 8.0% elongation and 6.2% reduction of area.

The stress-rupture properties of certain of the chromium-base alloys are superior to those of all other materials known to have been similarly tested.

INTRODUCTION

The objective of this investigation was to discover an alloy sufficiently resistant to the weakening effects of heat and to the corrosive attack of oxygen at high temperatures that it could serve in the form of a blade in gas turbines rotating at 25,000 to 30,000 rpm, with gas temperatures as high as 1600°F.

On the basis of certain simplifying assumptions and some exploratory experiments, described in progress reports, the work was directed—after the first seven months—toward a study of alloys of chromium. This decision was based upon a consideration of: the possibilities of alloys of all metals, the properties of the few alloys of chromium obtained in preliminary tests, the known difficulties of making chromium-rich alloys, and the brittle behavior in tension of the early chromium-base alloys. Three years of research have been spent on chromium-base alloys, yet it must be conceded that only a good start has been made in their development.

It is estimated that half of the total effort in connection with Contract OEMsr-457 was of necessity given to inventing suitable methods of melting, deoxidizing, casting, machining, and testing chromium-base alloys and to designing and constructing appropriate laboratory equipment. To save time, these developments were carried along with the survey of heat-resistant alloys of chromium. This concurrence brought forth one inevitable disadvantage: Because of the gradual improvement in techniques of making the alloys, comparison of the more recent and more highly purified alloys of one system with the older and less pure alloys of another system is rather difficult. Some judgment must therefore be used in appraising the data.

A list of the semiannual and cumulative reports submitted under Contract OEMsr-457 forms Appendix II of this report.

PROPERTIES OF CHROMIUM-BASE ALLOYS

Results of Stress-Rupture Tests and Hot Hardness Tests

The stress-rupture test is considered essential in discriminating among materials for gas turbines. All the promising alloys were therefore submitted to Dr. J. W. Freeman, of the University of Michigan, for stress-rupture test. In the stress-rupture tests of this investigation, a tensile test bar having a gauge length of one inch and a gauge diameter of 0.160" is heated to the testing temperature and loaded to produce the desired stress. The force producing the stress is kept constant until the specimen ruptures. The test data reported are: the time required to rupture, the original stress, the temperature, the per cent elongation of the gauge length, and the per cent reduction of area at the point of fracture. The stress-rupture test does not reveal a fundamental property of matter, but it does reproduce some of the essential stress conditions in a rotating turbine blade. Since the test is time-consuming, some more rapid method of making the primary selection of materials was necessary. One such method is the hot hardness test*. The hot hardness test was found very helpful as a guide, first in selecting the alloy base metel and later in selecting the elements for alloying with it.

The results of the hot-hardness and stress-rupture tests are presented in Tables I and II.

---

* The hot hardness test employed was similar to the Vickers hardness test, except that indentation was performed at some controlled elevated temperature in vacuum.

TABLE I

Hot Hardness Data

System	Heat No.	Composition***	Vickers Hardness Number					
			75	1112	1292	1600	1700	°F
			24	600	700	870	925	°C
Cr	16	~100% Cr	193			142		
Cr-Be	557	97Cr-3Be (.019C)*	563			305		
Cr-Co	403	88Cr-12Co (.019C)*	569**			132		
	261	55Cr-45Co (.020C)*				272		
Cr-Cb	384	90Cr-10Cb (.064C)*	531**			302		
	349	85Cr-15Cb (.142C)	668**			330		
	347	70Cr-30Cb (.223C)	710**			518		
Cr-Fe	271	74Cr-26Fe (.179C)*	450**			93		
Cr-Mo	268	90Cr-10Mo (.015C)*	426**			198		
	369	85Cr-15Mo (.019C)				253		
	386	85Cr-15Mo (.006C)*	490**			253		
	266	80Cr-20Mo (.008C)*	539**			280		
	128	70Cr-30Mo (.035C)	495			369		
Cr-Ni	393	85Cr-15Ni (.019C)*	800**			198		
Cr-Pt	343	90Cr-10Pt (.161C)*	390			237	198	
	340	83Cr-17Pt (.141C)	575**			280		
	339	70Cr-30Pt (.204C)	760**			323		
Cr-Ta	370	88Cr-12Ta (.032C)*	395**			270		
	342	83Cr-17Ta (.126C)*	490**			308		
	352	80Cr-20Ta (.034C)	600**			369		
	341	75Cr-25Ta (.186C)*	653**			362		
Cr-Th	558	95Cr-5Th (.011C)*	155	94	75	47		
Cr-Ti	429	93Cr-7Ti (.035C)*	351			236	230	
	424	90Cr-10Ti (.124C)*	392			229	225	
Cr-W	55	90Cr-10W				200		
	15	80Cr-20W	399			316		
	56	80Cr-20W				196		
	103	80Cr-20W (.17C)*	531			318		
	14	75Cr-25W	452			294		
	94	70Cr-30W (.10C)*	572			367		
	58	60Cr-40W (.19C)*				372		

* For more complete chemical analysis, see Appendix I.

** Microhardness (Vickers indenter, 24.4 gram load).

*** Unless otherwise indicated, tests were made on as-cast material. Throughout the paper composition is expressed as proportion by weight or weight per cent.

TABLE I (Cont.)

Hot Hardness Data

			Vickers Hardness Number @					
	Heat		75	1112	1292	1600	1700	°F
System	No.	Composition***	24	600	700	870	925	°C
Cr-W	95	70Cr-30W (.09C)*	552			338		
(Cont.)	12	67Cr-33W	488			413		
	4	50Cr-50W	625			286		
	13	40Cr-60W	465			437		
	7	33Cr-67W	513			338		
Cr-V	389	90Cr-10V (.169C)*	444**			296		
	396	85Cr-15V (.064C)*	357			313	286	
	390	80Cr-20V (.117C)*	493**			300		
Cr-Zr	556	97Cr-3Zr (.005C)*	190	143	141	132		
	422	90Cr-10Zr (.131C)*	262			185	174	
	430	90Cr-10Zr (.030C)	249			197	193	
	397	80Cr-20Zr (.021C)	600**			366		
Cr-Cb-Fe	570	60Cr-20Cb-20Fs(.014C)	677	576	524	286		
	623	60Cr-10Cb-30Fe(.019C)*	533	426	389	172	130	
Cr-Co-Fe	568	60Cr-20Co-20Fe(.009C)*	503	291	165	122	80	
Cr-Co-Mo	447	90Cr-5Co-5Mo (.091C)*	409			202	185	
	446	70Cr-25Co-5Mo (.047C)*	560			172	129	
	452	70Cr-10Co-20Mo(.025C)*	503			326	288	
	441	60Cr-20Co-20Mo(.038C)*	657			386	318	
	451	58Cr-28Co-14Mo(.084C)	858			469	396	
	472	56Cr-10Co-34Mo(.020C)*	572			508	434	
Cr-Co-W	381	75Cr-10Co-15W (.014C)*	630**			253		
	379	70Cr-15Co-15W (.032C)*	700**			218		
	377	65Cr-10Co-25W (.005C)*	735**			310		
	378	63Cr-17Co-20W (.161C)	800**			438		
	380	63Cr-17Co-20W (.029C)	800**			308		
	376	60Cr-23Co-17W (.210C)*	825**			359		
	392	60Cr-20Co-20W (.017C)*	800**			336		
	373	60Cr-15Co-25W (.003C)*	800**			359		
	375	60Cr-15Co-25W(.127C)*	1000**			407		
	374	60Cr-15Co-25W (.153C)*	780**			356		
Cr-Fe-Mo	543	70Cr-25Fe-5Mo (.016C)*	411	374	258	111		
	547	70Cr-20Fe-10Mo(.044C)*	446	400	334	186		
	548	70Cr-15Fe-15Mo(.035C)*	470	423	366	253		

* For more complete chemical analysis, see Appendix I.

** Microhardness (Vickers indenter, 24.4 gram load).

*** Unless otherwise indicated, tests were made on as-cast material. Throughout the paper composition is expressed as proportion by weight or weight per cent.

TABLE I (Cont.)

Hot Hardness Data

System	Heat No.	Composition***	Vickers Hardness Number @				
		°F	75	1112	1292	1600	1700
		°C	24	600	700	870	925
Cr-Fe-Mo (Cont.)	418	70Cr-13Fe-17Mo(.027C)*	511			282	
	531	65Cr-30Fe-5Mo (.048C)*	409	403	260	116	
	420	65Cr-25Fe-10Mo(.032C)*	473			220	173
	363	65Cr-20Fe-15Mo(.057C)*	488			229	216
	549	65Cr-15Fe-20Mo(.048C)*	473	450	438	293	
	471	60Cr-35Fe-5Mo (.038C)*	363			117	84
	471HT	60Cr-35Fe-5Mo (.038C)*	413			128	103
	L-62	60Cr-35Fe-5Mo		356	246	110	
	530	60Cr-30Fe-10Mo(.040C)*	408	386	291	149	
	554	60Cr-25Fe-15Mo(.037C)*	468	430	376	214	
	559	60Cr-25Fe-15Mo(.043C)*	468	420	369	207	
	561	60Cr-25Fe-15Mo(.221C)*	503	442	362	192	
	571	60Cr-25Fe-15Mo(.095C)*	503	434	353	208	148
	617	60Cr-25Fe-15Mo(.073C)*	579	518	403	210	152
	619	60Cr-25Fe-15Mo	530	455	334	195	141
	620	60Cr-25Fe-15Mo(.013C)*	455	482	308	198	153
	621	60Cr-25Fe-15Mo(.307C)*	530	432	336	220	180
	404	60Cr-20Fe-20Mo(.045C)*	600**			296	
	469	60Cr-15Fe-25Mo(.027C)*	498	430	396	296	274
	132	60Cr-10Fe-30Mo(.077C)	481			382	
	419	60Cr-10Fe-30Mo(.021C)*	655**			317	
	545	55Cr-40Fe-5Mo (.037C)*	390	303	220	77	
	479	55Cr-35Fe-10Mo(.040C)*	433	362	288	148	112
	479-1	55Cr-35Fe-10Mo(.040C)*	657			223	167
	414	55Cr-30Fe-15Mo(.062C)*	482	382	328	223	171
	476HT	55Cr-30Fe-15Mo(.066C)*	690			260	214
	537	55Cr-25Fe-20Mo(.030C)*	478	416	359	247	
	539	55Cr-20Fe-25Mo(.011C)*	508	529	382	256	
	417	55Cr-15Fe-30Mo(.036C)	514			382	362
	478	50Cr-45Fe-5Mo (.019C)*	366	253	167	75	61
	478HT	50Cr-45Fe-5Mo (.019C)*	665			186	126
	533	50Cr-40Fe-10Mo(.032C)*	378	320	247	111	
	470	50Cr-35Fe-15Mo(.075C)*	483			185	153
	470HT	50Cr-35Fe-15Mo(.075C)*	894			315	342
	535	50Cr-30Fe-20Mo(.011C)*	479	382	338	240	
	416	50Cr-25Fe-25Mo(.063C)*	552			291	278
	485HT	50Cr-25Fe-25Mo(.075C)*	757			442	274
	538	50Cr-20Fe-30Mo(.066C)	533	518	450	394	
	552	50Cr-20Fe-30Mo(.013C)*	525	490	430	326	
	445	50Cr-10Fe-40Mo(.025C)*	519			366	330

* For more complete chemical analysis and description of the alloys, see Appendix I.

** Microhardness (Vickers indenter, 24.4 gram load).

*** Unless otherwise indicated, tests were made on as-cast material. Throughout the paper composition is expressed as proportion by weight or weight per cent.

TABLE I (Cont.)

Hot Hardness Data

System	Heat No.	Composition***	Vickers Hardness Number @				
			75 24	1112 600	1292 700	1600 870	1700 °F 925 °C
Cr-Fe-Mo	434	45Cr-20Fe-35Mo(.093C)*	579			389	359
(Cont.)	474	40Cr-50Fe-10Mo(.026C)*	336			474	407
	550	40Cr-55Fe-5Mo (.029C)*	309	225	122	227	
	433	32Cr-29Fe-38Mo(.054C)	870			744	722
	553	30Cr-65Fe-5Mo (.002C)*	263	166	104	34	
	437	20Cr-50Fe-30Mo(.106C)	772			665	541
	440	13Cr-65Fe-22Mo(.017C)*	579			161	172
Cr-Fe-Ni	567	60Cr-20Fe-20Ni(.013C)*	724	450	268	94	
	257	50Cr-3Fe-47Ni (.071C)*	331**			96	
Cr-Fe-Ta	449	65Cr-25Fe-10Ta(.112C)*	478			231	202
	448	60Cr-20Fe-20Ta(.126C)*	554			256	200
	463	57Cr-28Fe-15Ta(.077C)*	493			185	137
	461	50Cr-25Fe-25Ta(.097C)*	560			213	167
Cr-Fe-W	313	70Cr-15Fe-15W (.021C)*	570**			216	
	409	65Cr-20Fe-15W (.010C)*	600**			206	
	412	60Cr-30Fe-10W (.021C)*	580**			156	
	312	60Cr-25Fe-15W (.071C)*	575**			184	
	272	60Cr-20Fe-20W (.094C)*	602**			226	
	356	60Cr-25Fe-15W (.063C)*	468			210	167.
	L-41	60Cr-25Fe-15W	429	326	268	178	
	PP152	60Cr-25Fe-15W	536			342	286
	314	60Cr-20Fe-20W (.019C)*	595**			253	
	382	60Cr-20Fe-20W (.070C)*	598**			218	
	387	60Cr-20Fe-20W (.043C)*	620**			253	
	91	60Cr-15Fe-25W (.046C)*	462			294	
	315	60Cr-12Fe-28W (.016C)*	652**			310	291
	130	60Cr-10Fe-30W (.034C)	503			319	
	408	55Cr-25Fe-20W (.041C)*	585**			237	
	388	53Cr-15Fe-32W (.041C)	730**			369	
	321	52Cr-21Fe-27W (.092C)*	630**			305	
	400	52Cr-11Fe-37W (.008C)*	625**			359	
	407	51Cr-19Fe-30W (.021C)*	650**			351	
	320	50Cr-25Fe-25W (.098C)*	620			285	251
	335	47Cr-32Fe-21W (.084C)*	529			219	179
Cr-Fe-U	421	80Cr-15Fe-5U (.156C)*	397			179	134
Cr-Fe-Zr	622	60Cr-30Fe-10Zr(.108C)*	483	300	244	129	99
Cr-Ni-W	328	75Cr-10Ni-15W (.186C)*	715				282
	327	60Cr-20Ni-20W (.261C)*	835			291	181
	324	60Cr-15Ni-25W (.175C)*	870			356	229
	322	50Cr-25Ni-25W (.036C)*				313	

* For more complete chemical analysis, see Appendix I.

** Microhardness (Vickers indenter, 24.4 gram load).

*** Unless otherwise indicated, tests were made on as-cast material. Throughout the paper composition is expressed as proportion by weight or weight per cent.

TABLE II

Stress-Rupture Properties of Chromium-Base Alloys*

System	No.	Composition, %**	Stress psi.	Temp. °F.	Time for Rupture	% El	% RA	Remarks
Pure Cr	269	~100Cr (.044C)	20,000	1600	1 Min.	3.5	3.7	
Cr-Be	428	99Cr-.06Be (.052C)	21,000	1600		1.0	0	Broken during loading
Cr-Co	403	88Cr-12Co (.019C)	24,000	1600	27 Min.	6	5.2	
	262	80Cr-20Co (.327C)	20,000	1600	1.75 Hrs.	7	11.4	
	273	65Cr-35Co (.254C)	20,000	1600				Broken during loading
Cr-Cb	384	90Cr-10Cb (.064C)	24,000	1600	215 Hrs.	0	0	
	354	85Cr-15Cb (.141C)	20,000	1600				Broken during loading
	347	70Cr-30Cb (.224C)	20,000	1600	48.5 Hrs.	<1	0	
Cr-Fe	271	74Cr-26Fe (.179C)	20,000	1600	1 Min.	1.0	1.8	
	256	46Cr-54Fe (.039C)	6,825	1500		10.5	13.5	Broken during heating
Cr-Mo	268	90Cr-10Mo (.015C)	20,000	1600	29.5 Hrs.	1.7	0	
	386	85Cr-15Mo (.008C)	24,000	1600	126 "	2.0	0	
	266	80Cr-20Mo (.008C)	20,000	1600	253 "	1	0	
	267	62Cr-38Mo (.008C)	20,000	1600	84 "	<1	0	
Cr-Ni	393	85Cr-15Ni (.019C)	24,000	1600	1 Min.	1.0	0	
	258	72Cr-28Ni (.246C)	20,000	1600	20 Min.	3.7	1.7	
Cr-Pt	343	90Cr-10Pt (.161C)	20,000	1600	35.5 Hrs.	2.0	0	
	383	88Cr-12Pt (.035C)	24,000	1600	19.0 "	2.0	1.4	
Cr-Ta	370	88Cr-12Ta (.032C)	24,000	1600				Broken during loading
	371	80Cr-20Ta (.109C)	24,000	1600	1091 Hrs.	2.0	0	
	341	75Cr-25Ta (.186C)	20,000	1600	873 "	<1	0	

* All stress-rupture tests performed at Department of Engineering Research, University of Michigan.

** For more complete chemical analysis of all except the 100% Cr, see Appendix I.

TABLE II (Cont.)

Stress-Rupture Properties of Chromium-Base Alloys

System	No.	Composition, %	Stress psi.	Temp. °F.	Time for Rupture	% El	% RA	Remarks
Cr-Ti	429	93Cr-7Ti (.035C)*						Broken when set in furnace
	424	90Cr-10Ti (.124C)*	24,000	1600	30 Sec.	0	0	
Cr-W	106	80Cr-20W (.23C)*	20,000	1600				Fractured during loading
	117	70Cr-30W (.028C)	20,000	1600				Fractured during loading
	123	70Cr-30W (.025C)*	22,000	1600	78.5 Hrs.	1-2	0	
	142	70Cr-30W (.015C)	22,000	1600				Fractured during loading
Cr-V	389	90Cr-10V (.169C)*	7,470	1600	5 Min.	0	0	Fractured during loading
	396	85Cr-15V (.064C)*	24,000	1600	7 Hrs.	0	0	
	390	80Cr-20V (.171C)*	22,000	1600		0	0	Fractured during loading
Cr-Co-Mo	447	90Cr-5Co-5Mo (.091C)*	24,000	1600	24 Hrs.	2.0	0	
	446	70Cr-25Co-5Mo(.047C)*	24,000	1600	3.25 Hrs.	11.0	16.5	
	452	70Cr-10Co-20Mo(.025C)*	24,000	1600	271 "	4.0	3.7	
	**441-1	60Cr-20Co-20Mo(.038C)*	24,000	1600	334 "	7.0	11.5	
	**441-2	60Cr-20Co-20Mo(.038C)*	16,000	1600				Fractured during loading
	472	58Cr-10Co-32Mo(.020C)*	24,000	1600	564 "	2.0	0	
Cr-Co-W	381	80Cr-5Co-15W (.014C)*	24,000	1600	74 "	2.0	0	
	379	70Cr-15Co-15W (.032C)*	24,000	1600	40 "	4.0	1.4	
	377	70Cr-10Co-20W (.005C)*	24,000	1600	5 Sec.	0	0	
	392	60Cr-20Co-20W (.017C)*	24,000	1600	124 Hrs.	1.5	0	
	373	60Cr-15Co-25W (.003C)*	24,000	1600	72 "	1.0	1.2	
	375	60Cr-15Co-25W (.127C)*	24,000	1600	630 "	1.0	0.6	
	374	58Cr-14Co-28W (.153C)*	24,000	1600	218 "	2.0	1.2	
Cr-Cb-Fe	623	60Cr-30Fe-10Cb(.018C)*	20,000	1600	6 "	6.0	11.2	
Cr-Fe-Mo	543	70Cr-25Fe-5Mo (.016C)*	20,000	1600	59 Min.	3.0	0	
	547	70Cr-20Fe-10Mo(.044C)*	20,000	1600	7 Hrs.	1.0	2.4	
	548	70Cr-15Fe-15Mo(.035C)*	20,000	1600	51.5 Hrs.	1.5	0	
	418	70Cr-13Fe-17Mo(.027C)*	20,000	1600	340 "	3.5	2.0	

*For more complete chemical analysis and description of the alloys, see Appendix I.

**The designations with four digits distinguish between test bars cast from the same heat (i.e., from the same batch of molten metal).

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TABLE II (Cont.)
Stress-Rupture Properties of Chromium-Base Alloys

System	No.	Composition	Stress psi.	Temp. °F.	Time for Rupture	% El	% RA	Remarks
Cr-Fe-Mo (Cont.)	531	65Cr-30Fe-5Mo (.048C)*	20,000	1600	3 Hrs.	10.0	9.8	
	420	65Cr-25Fe-10Mo (.032C)*	20,000	1600	36 "	10.5	14.3	
	678-1	65Cr-25Fe-10Mo (.030C)*	50,000	1350	113 Hrs.	13.0	13.0	
	363	65Cr-20Fe-15Mo (.057C)*	20,000	1600	88 "	6.0	7.3	
	549	65Cr-15Fe-20Mo (.048C)*	20,000	1600	491 "	10.0	6.2	
	471	60Cr-35Fe-5Mo (.038C)*	24,000	1600	32 Min.	16.0	16.0	
	546-1	60Cr-35Fe-5Mo (.032C)*	20,000	1600	1.5 Hrs.	22.0	20.4	
	L-64	60Cr-35Fe-5Mo (.058C)*	20,000	1600	1.1 "	26	22.4	Forged
	608	60Cr-30Fe-10Mo (.033C)*	50,000	1350	38 "	40	35	
	530	60Cr-30Fe-10Mo (.040C)*	20,000	1600	4 "	26.0	24.6	
	530-1	60Cr-30Fe-10Mo (.040C)*	50,000	1350	39 "	48	44	
	518	60Cr-25Fe-15Mo (.016C)*	20,000	1600	76 "	12.0	13.6	
	518-HT	60Cr-25Fe-15Mo (.016C)*	20,000	1600	142 "	22	33	
	522	60Cr-25Fe-15Mo (.050C)*	45,000	1350	450 "	9	9	Overheated to 1800°F.
	526	60Cr-25Fe-15Mo (.101C)*	20,000	1600	54 "	26.0	21.6	
	554-1	60Cr-25Fe-15Mo (.037C)*	20,000	1600	132 "	22.0	24.8	
	554-2	60Cr-25Fe-15Mo (.037C)*	50,000	1350	1414 "	8	6.2	
	559	60Cr-25Fe-15Mo (1.2Si)*	20,000	1600	222 "	13	25.7	
	561	60Cr-25Fe-15Mo (.221C)*	20,000	1600	68.5 "	11.0	9.7	Fractured in threads
	571	60Cr-25Fe-15Mo (.095C)*	20,000	1600	70 "	25.0	23.5	
	599	60Cr-25Fe-15Mo (.105C)*	20,000	1600	85 "	41.0	42.5	
	612-1	60Cr-25Fe-15Mo (.013C)*	20,000	1600	50 "	13.0	12.2	
	612-2	60Cr-25Fe-15Mo (.013C)*	50,000	1350	484 "	9	9	
	621	60Cr-25Fe-15Mo (.307C)*	20,000	1600	70.5 "	14.0	14.5	
	634-1	60Cr-25Fe-15Mo (.70Si)*	50,000	1350	985 "	5	5	
	655-1	60Cr-25Fe-15Mo (.016C)*	50,000	1350	530 "	19	17	

* For more complete chemical analysis and description of the alloys, see Appendix I.

TABLE II (Cont.)
Stress-Rupture Properties of Chromium-Base Alloys

System	No.	Composition, %	Stress psi.	Temp. °F.	Time for Rupture	% El	% RA	Remarks
Cr-Fe-Mo	657-1	60Cr-25Fe-15Mo (.082C)*	55,000	1350	347 Hrs.	11	11	
(Cont.)	679-1	60Cr-25Fe-15Mo (.022C)*	63,800	1350	182 "	5		Fractured in threads
	679-2	60Cr-25Fe-15Mo (.022C)*	55,000	1350	611 "	5	6	
	404	60Cr-20Fe-20Mo (.045C)*	20,000	1600	331 "	2.0	2.4	
	618-1	60Cr-20Fe-20Mo (.011C)*	24,000	1600	229 "	8.0	6.8	
	618-2HT	60Cr-20Fe-20Mo (.011C)*	24,000	1600	280 "	9.0	9.3	
	469-1	60Cr-15Fe-25Mo (.027C)*	20,000	1700	76 "	5.5	5.0	
	469-2	60Cr-15Fe-25Mo (.027C)*	24,000	1600	478 "	5.0	5.0	
	469-3	60Cr-15Fe-25Mo (.027C)*	30,000	1600	291 "	5.0	5.0	
	469-4	60Cr-15Fe-25Mo (.027C)*	20,000	1600	1042 "	9	12	
	613-1	60Cr-15Fe-25Mo (.049C)*	37,500	1600	65 "	1.0	1.2	
	613-2	60Cr-15Fe-25Mo (.049C)*	35,000	1600	371 "	5.0	3.8	
	635-1	60Cr-15Fe-25Mo (.129C)*	30,000	1600	290 "	9.5	7.6	
	635-2HT	60Cr-15Fe-25Mo (.129C)*	26,500	1600	472 "	9.0	8.6	Test interrupted at 276 h
	636-1	60Cr-15Fe-25Mo (.157C)*	30,000	1600	132 "	4.0	8.5	
	636-2HT	60Cr-15Fe-25Mo (.157C)*	30,000	1600	316.5 "	3.0	2.4	Test interrupted at 248 h
	667-1	60Cr-15Fe-25Mo (.021C)*	30,000	1600	523 "	3.0	1.2	Test interrupted at 401 h
	667-2HT	60Cr-15Fe-25Mo (.021C)*	30,000	1600	336 "	4.0	1.2	
	668-1	60Cr-15Fe-25Mo (.032C)*	30,000	1600	410 "	5.0	4.9	Test interrupted at 42 h
	668-2HT	60Cr-15Fe-25Mo (.032C)*	30,000	1600	430.5 "	6.0	6.3	
	668-3HT	60Cr-15Fe-25Mo (.032C)*	30,000	1600	145 "	8.0	7.4	
	444-1	60Cr-5Fe-35Mo (.019C)*	24,000	1600	18 "	1	0	
	444-2	60Cr-5Fe-35Mo (.019C)*	24,000	1600	13.5 "	0	0	Flaw in specimen
	419-1	60Cr-10Fe-25Mo (.021C)*	20,000	1600	60 "			Pulled out of adapter
	419-2	60Cr-10Fe-25Mo (.021C)*	24,000	1600	583 "	2.0	1.2	
	632	57Cr-15Fe-28Mo (.064C)*	30,000	1600	390 "	4.3	2.6	Test interrupted at 254 h
	545	55Cr-40Fe-5Mo (.037C)*	20,000	1600	35 Min.	34	42.8	
	528	55Cr-35Fe-10Mo (.036C)*	20,000	1600	9 Hrs.	59.0	52.3	
	528-HT	55Cr-35Fe-10Mo (.036C)*	20,000	1600	13.5 "	64	58.6	
	414	55Cr-30Fe-15Mo (.062C)*	20,000	1600	60 "	20.0	29.2	

* For more complete chemical analysis and description of the alloys, see Appendix I.

TABLE II (Cont.)

Stress-Rupture Properties of Chromium-Base Alloys

System	No.	Composition, %	Stress psi.	Temp. °F.	Time for Rupture	% El	% RA	Remarks
Cr-Fe-Mo (Cont.)	476-2	55Cr-30Fe-15Mo (.066C)*	15,000	1600				Fractured during loading
	537	55Cr-25Fe-20Mo (.030C)*	20,000	1600	233 Hrs.	40.0	40.8	Overheated to 1800°F.
	539	55Cr-20Fe-25Mo (.011C)*	24,000	1600	413 "	6.0	8.5	
	417	55Cr-15Fe-30Mo (.036C)*	20,000	1600	1368 "	1.0	0	Pulled out of adapter
	534	50Cr-35Fe-15Mo (.030C)*	20,000	1600	38 "	24	34.2	
	534-1	50Cr-35Fe-15Mo (.030C)*	50,000	1350	270.5 "	10	13.5	
	535	50Cr-30Fe-20Mo (.011C)*	20,000	1600	172.5 "	53.0	55.8	
	416	50Cr-25Fe-25Mo (.063C)*	20,000	1600	185 "	11.0	11.7	Overheated 12 h @ 1660°F.
	552	50Cr-20Fe-30Mo (.013C)*	24,000	1600	814 "	2.0	1.2	
	445	50Cr-10Fe-40Mo (.025C)*	24,000	1600	1246 "	<3	0	
	540	50Cr-45Fe-5Mo (.013C)*	20,000	1600	5.5 "	22	26.9	
	533	50Cr-40Fe-10Mo (.032C)*	20,000	1600	4 "	88	56.1	
	629	45Cr-45Fe-10Mo (.010C)*						Fractured during loading
	633	45Cr-40Fe-15Mo (.047C)	20,000	1600	52 "	13	17	
	630	45Cr-35Fe-20Mo (.016C)*	19,000	1600				Fractured during loading
	631	45Cr-25Fe-30Mo (.071C)						Fractured during loading
	434-1	45Cr-20Fe-35Mo (.093C)*	24,000	1600	41 "			Adapter broke
	434-2	45Cr-20Fe-35Mo (.093C)*	24,000	1600	807 "	2.0	0	Controller failed
	550	40Cr-55Fe-5Mo (.029C)*	20,000	1600	21 "	2.0	3.7	
	553	30Cr-65Fe-5Mo (.002C)*	20,000	1600	9 Min.	10	18.3	
Cr-Fe-Ni	257	50Cr-3Fe-47Ni (.071C)*	20,000	1600	7 Min.	1.6	2.8	
Cr-Fe-Ta	449	65Cr-25Fe-10Ta (.112C)*	24,000	1600	27 Hrs.	2.0	3.6	
	448	60Cr-20Fe-20Ta (.126C)*	24,000	1600	21 "	5.0	4.8	
	463	57Cr-28Fe-15Ta (.077C)*	24,000	1600	4 "	12.0	9.9	
	461	50Cr-25Fe-25Ta (.097C)*	24,000	1600	11 "	8	10.9	

* For more complete chemical analysis and description of the alloys, see Appendix I.

TABLE II (Cont.)

Stress-Rupture Properties of Chromium-Base Alloys

System	No.	Composition, %	Stress psi.	Temp. °F.	Time for Rupture	% El	% RA	Remarks
Cr-Fe-W	177A	80Cr-15Fe-5W (.05C)*	20,000	1600	6.5 Hrs.	1.0	<1	
	97	75Cr-5Fe-20W (.43C)	17,500	1600				Fractured during loading
	309	70Cr-20Fe-10W (.027C)*	20,000	1600	40 "	5.7	5.0	
	313-1	70Cr-15Fe-15W (.021C)*	20,000	1600	105 "			Adapters failed
	313-2	70Cr-15Fe-15W (.021C)*	24,000	1600	89 "	2.0	1.4	
	409	70Cr-15Fe-15W (.010C)*	24,000	1600	37 "	1.0	2.5	
	176	70Cr-10Fe-20W (.02C)	20,000	1600	17 "	0	0	
	406	70Cr-10Fe-20W	22,000	1600				Fractured during loading
	169	70Cr-5Fe-25W (.028C)*	20,000	1600	915 "	0	0	
	412	60Cr-30Fe-10W (.021C)*	24,000	1600	9.5 "	12.0	17.3	
	168-C	60Cr-30Fe-10W (.112C)*	20,000	1600	48 "	22.0	28.4	
	168-D	60Cr-30Fe-10W (.112C)*	20,000	1600	13 "	< 2.0	0	
	312	60Cr-25Fe-15W (.071C)*	20,000	1600	54 "	4.0	8	
	356	60Cr-25Fe-15W (.063C)*	20,000	1600	108 "	3.0	3.6	
	272	60Cr-20Fe-20W (.094C)*	20,000	1600	205.5 "	2.4	1.2	
	311	60Cr-20Fe-20W (.026C)*	20,000	1600	412 "	3	1.3	
	314	60Cr-20Fe-20W (.019C)*	20,000	1600	491 "	3	2.4	
	382	60Cr-20Fe-20W (.070C)*	24,000	1600	110 "	7	5.5	
	387-1	60Cr-20Fe-20W (.043C)*	24,000	1600	62 "	1	0	
	387-2	60Cr-20Fe-20W (.043C)*	22,000	1600	74 "	1	0	
	91	60Cr-15Fe-25W (.046C)*	17,500	1600	643 "	3.7	1.0	
	162	60Cr-15Fe-25W (.051C)*	20,000	1600	479 "	< 1	<1	
	166	60Cr-15Fe-25W (.024C)*	20,000	1600	555 "	< 1	0	
	167	60Cr-15Fe-25W (.10C)	20,000	1600	632 "	< 1	0	
	130	60Cr-10Fe-30W (.034C)	20,000	1600	6 "	2.9	1.3	
	315	60Cr-10Fe-30W (.016C)*	20,000	1600	1787 "	2.2	1.1	
	319	55Cr-25Fe-20W (.066C)*	20,000	1600	240 "	2.5	0	
	399-1	55Cr-20Fe-25W (.024C)*	24,000	1600	179 "	<1	0	
	399-2	55Cr-20Fe-25W (.024C)*	20,000	1600	324 "	1	1.1	
	399-3	55Cr-20Fe-25W (.024C)*	16,000	1600	1366 "	1	0	

* For more complete chemical analysis and description of the alloys, see Appendix I.

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TABLE II (Cont.)

Stress-Rupture Properties of Chromium-Base Alloys

System	No.	Composition, %	Stress psi.	Temp. °F.	Time for Rupture	% El	% RA	Remarks
Cr-Fe-W (Cont.)	400	55Cr-10Fe-35W (.008C)*	20,000	1600				Fractured during loading
	408	50Cr-30Fe-20W (.041C)*	24,000	1600	134 Hrs.	1.5	0	
	320	50Cr-25Fe-25W (.098C)*	20,000	1600	214 "	3.0	0.6	
	321	50Cr-20Fe-30W (.092C)*	20,000	1600	227 "	1.0	0.5	
	407	50Cr-20Fe-30W (.032C)*	24,000	1600	350.5 "	1.0	0	
	317	50Cr-15Fe-35W (.02C)	20,000	1600	67 "			Fractured in threads
	395	50Cr-15Fe-35W (.018C)	24,000	1600	340 "	1	0	
	335	45Cr-35Fe-20W (.084C)*	20,000	1600	84 "	3.0	3.9	
Cr-Fe-U	421	80Cr-15Fe-5U (.156C)*	24,000	1600	42 Min.			Fractured in threads
Cr-Ni-W	350	77Cr-7Ni-16W (.032C)*	24,000	1600	45 Min.	1.0	0	
	330	70Cr-15Ni-15W (.209C)*	10,000	1550	14 Hrs.	3.8	1.4	Fractured while coming to temperature
	326	65Cr-10Ni-25W (.142C)*	20,000	1600	1 "	3.0	0	
	327	60Cr-20Ni-20W (.261C)*	20,000	1600	3/4 "	3.0	2.5	
	324	60Cr-15Ni-25W (.175C)*	20,000	1600	3 "	3.0	1.0	
	351	50Cr-20Ni-30W (.040C)*	24,000	1600	12 Min.	2.0	2.6	

* For more complete chemical analysis and description of the alloys, see Appendix I.

NOTE: The following Stress-Rupture Data were received after the writing of this report:

System	No.	Composition, %	Stress psi.	Temp. °F.	Time for Rupture	% El	% RA
Cr-Fe-Mo	655-2HT	60Cr-25Fe-15Mo (.02C)*	50,000	1350	434 Hrs.	10	12
	679-3	60Cr-25Fe-15Mo (.028)*	70,000	1350	76 "	4	6

Some of the stress-rupture tests were incomplete because the specimen broke during loading, during heating, or during installation. Since great care was always taken in testing, it is safe to infer that if the specimen broke by any of the three methods mentioned, that particular alloy was too brittle to survive a tiny shock.

Density

The observed and computed densities of some chromium-base alloys are recorded in Table III. The densities computed according to the relation

$$\text{Density of alloy} = \frac{100}{\frac{\text{Wt-\% of A}}{\text{Density of A}} + \frac{\text{Wt-\% of B}}{\text{Density of B}} + \ldots}$$

are within 2% of the observed densities.

Those alloys that are not high in tungsten have lower densities than the cobalt-, iron-, and nickel-base alloys.

Young's Modulus

From optical measurements of deflections of a cantilever beam and electrical strain gauge measurements of a tensile bar, Young's moduli of some chromium-base alloys have been computed; they are given in Table IV.

Coefficient of Thermal Expansion

The coefficient of thermal expansion of one alloy (65Cr-35W) in the temperature range 80 to 1650°F. was determined to be 5.24×10^{-6} per °F.

Corrosion Resistance

Mostly as a result of incidental observations made during various tests and chemical analyses performed on chromium-base alloys, some information on the corrosion resistance of chromium alloys has been obtained.

TABLE III

Density of Some Chromium Alloys

No.	Composition, %*	Condition	Density, g/cc Computed	Density, g/cc Observed
73	70Cr-30W (.026C)	As-cast	8.82	8.68
L-5VP	57Cr-23Fe-20Mo (.018C)		7.74	7.7476
469	60Cr-15Fe-25Mo (.027C)	As-cast	7.80	
445**	50Cr-10Fe-40Mo (.025C)	"	8.16	
533***	50Cr-40Fe-10Mo (.032C)	"	7.61	
399-2	57Cr-21Fe-22W (.024C)	"	8.44	8.4541
399-4	57Cr-21Fe-22W (.024C)	Held 324 h @ 1600°F.		8.5670
212-M1	47Cr-23Fe-27W-3Mo (.026C)	As-cast	8.90	8.7831
214-M1	45Cr-23Fe-29W-3Mo (.05C)	"	9.03	8.9251
216-M1	45Cr-23Fe-29W-3Mo (.029C)	"	9.03	8.9252
239-M1	58Cr-20Fe-20W-2Mo (.018C)	"	8.36	8.2688
240-M1	54Cr-22Fe-22W-2Mo (.021C)	"	8.52	8.4290
243-M1	52Cr-22Fe-24W-2Mo (.018C)	"	8.65	8.6244
246-M1	56Cr-20Fe-22W-2Mo (.013C)	"	8.49	8.4164
249-M1	59Cr-19Fe-20W-2Mo (.016C)	"	8.34	8.3100

* For more complete chemical analysis and description of the alloys, see Appendix I.

** Strongest chromium alloy at 1600°F.

*** Most ductile chromium alloy at 1600°F.

TABLE IV

Modulus of Elasticity of Some Chromium Alloys

No.	Composition, %*	Condition	Modulus, psi	Type of Test
471	60Cr-35Fe-5Mo	48 Hrs. @ 1600°F.	32,600,000	Cantilever beam
476	55Cr-30Fe-15Mo	4 " " "	35,820,000	" "
479-1	55Cr-35Fe-10Mo	4 " " "	32,960,000	" "
479-2	55Cr-35Fe-10Mo	168 " " "	35,960,000	" "
480	60Cr-20Fe-20Mo	As-cast	35,300,000	" "
485	52Cr-24Fe-24Mo	1/2 Hr. @ 1600°F.	32,670,000	" "
480-1	60Cr-20Fe-20Mo	As-cast	34,780,000	" "
480-2	60Cr-20Fe-20Mo	As-cast	35,860,000	" "
514-A	60Cr-20Fe-20W	As-cast	36,500,000	Elec.strain gage
514-B	60Cr-20Fe-20W	As-cast	37,000,000	" " "
514-C	60Cr-20Fe-20W	As-cast	37,200,000	" " "

* For more complete chemical analysis and description of the alloys, see Appendix I.

The stress-rupture tests, which were performed in air, indicate that all the alloys except the chromium-vanadium alloys are sufficiently resistant to oxidation that their load-carrying ability at 1600°F. is not impaired by this type of corrosion. Many metallographic examinations have been made of tested stress-rupture bars and no evidence of intergranular corrosion has been found.

Special tests have shown that the 50Cr-25Fe-25Mo alloy resists the attack of lead oxide and lead bromide at 1600°F.

During chemical analysis, the chromium-iron-molybdenum alloys containing at least 20% molybdenum resisted attack by all combinations of sulfuric, nitric, and hydrochloric acids.

A few corrosion tests were made in hydrochloric acid at room temperature. The results are recorded in Table V. Apparently, carbon above 0.10% reduces resistance to hydrochloric acid.

METALLOGRAPHY OF CHROMIUM-IRON-MOLYBDENUM ALLOYS

Only the chromium-iron-molybdenum alloys have been studied sufficiently for a discussion of their metallography, and even here the sum of knowledge is not large.

Chromium, iron, and molybdenum are transition metals; they all crystallize in the body-centered-cubic arrangement. Only iron is certainly allotropic. The transformation from body-centered-cubic to face-centered-cubic, which occurs in iron at 1670°F. (910°C.) on heating, does not occur in iron-molybdenum alloys containing more than 3% molybdenum nor in iron-chromium alloys containing more than 17% chromium. Therefore, in chromium-iron-molybdenum alloys containing more than 50% chromium it is to be

TABLE V

Rate of Corrosion of Chromium-Base Alloys in 50% Hydrochloric Acid

No.	Composition, %	Original Weight, g	Final Weight, g	Loss in Weight mg/sq dm/day***
122	77Cr-23W (.11C)	2.3063	0.7909**	79,700
316	74Cr-6Fe-20W (.007C)*	2.5057	2.5059	None
369	85Cr-15Mo (.019C)	5.7840	5.7842	None
378	62Cr-17Co-21W (.161C)	2.8878	1.2554**	86,400
386	83Cr-17Mo (.006C)*	2.6955	2.6958	None
388	53Cr-15Fe-32W (.041C)	3.5933	3.5936	None
400	52Cr-11Fe-37W (.008C)*	2.7281	2.7305	None
415	64Cr-9Fe-27Mo (.024C)	6.4479	6.4483	None
417	56Cr-15Fe-29Mo (.036C)	7.4864	7.4869	None
418	69Cr-13Fe-18Mo (.027C)*	0.7205	0.7209	None
433	32Cr-30Fe-38Mo (.054C)	1.4548	1.4433	5.92
434	43Cr-21Fe-36Mo (.093C)*	8.1276	8.1279	None
438	52Cr-9Fe-39Mo (.003C)	2.5752	2.5745	0.02
439	59Cr-5Fe-36Mo (.022C)	1.6025	1.6039	None
441	60Cr-20Co-20Mo (.038C)*	4.4762	4.4766	None
				—

* For more complete chemical analysis and description of the alloys, see Appendix I.

** After seven days.

*** Samples held 100 days.

expected that in addition to intermetallic compounds, only body-centered-cubic, chromium-rich solid solutions will be found. No contradictory evidence has come to light.

The atomic radius of iron is only 0.8% smaller than the atomic radius of chromium, and the atomic radius of molybdenum is only 8.8% larger than that of chromium. It is to be expected then that chromium-base alloys with iron and molybdenum have melting points not much below the melting point of chromium. This is true if the impurities carbon, oxygen, nitrogen, and silicon are kept low.

Equilibrium diagrams have been satisfactorily established for the iron-molybdenum and the chromium-iron binary systems, but not for the chromium-molybdenum system. The chromium-molybdenum system has been reported in one instance as an eutectiferous series of the two terminal solid solutions[*] and in another instance as forming a continuous solid solution from 100% chromium to 100% molybdenum[**]. It was considered important to the present investigation to establish at least the general form of the chromium-molybdenum system. In order to save time and to reduce the effect of impurities to a minimum, a very pure sample of molybdenum and a very pure sample of chromium were prepared with all possible care. The two were press-welded together in vacuum at 2300°F. (1260°C.) and allowed to diffuse into each other at that temperature for twenty-eight days and furnace cooled. Thus a series of alloys, from 100% chromium to 100% molybdenum, was made. Beginning at the chromium end of the diffusion couple, successive layers (each 0.005" thick) were removed on planes parallel to the original molybdenum-chromium interface.

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[*] Siedschlag: Z. anorg. allg. Chem. 131:191 (1923)

[**] Kubaschewski and Schneider: Z. Elektrochem. 48:671-4 (1942)

As each layer was removed, the lattice parameter of the alloy at the newly exposed surface was determined. The width of the "diffusion zone" was about 1/8". The lattice parameter at 78°F. varied continuously from 2.8787 Å at the chromium end to 3.1407 Å at the molybdenum end. Metallographic examination of the diffusion zone disclosed no phase boundary. Likewise, metallographic examination of chromium-molybdenum stress-rupture bars tested for several hundred hours at 1600°F. revealed but one phase. From this evidence and from the unlikelihood of a compound in the system, because of the similarity of molybdenum to chromium, it is concluded that there is only one solid phase in the chromium-molybdenum system.

In the chromium corner of the chromium-iron-molybdenum system there is a body-centered cubic, chromium-rich solid solution and an as yet unidentified phase, which is probably an intermetallic compound or a superlattice and whose atomic structure is neither cubic nor hexagonal. The compound is therefore not the hexagonal Fe_3Mo_2 nor the hexagonal FeMo*, but it may be the FeCr tentatively identified in the iron-chromium system.

When the chromium-rich, chromium-iron-molybdenum alloys are chill cast, the compound does not form, but it precipitates on holding several hours at 1600°F. In general, the hardness of the alloys increases when precipitation occurs. This gain in hardness is retained, even after many hours at high temperatures.

Chromium-rich, chromium-iron-molybdenum alloys do not possess that most useful eutectoid inversion, as do iron-rich alloys. Nor is there any other phase change to enable grain refinement by heat treatment in the solid state. Therefore, small amounts of carbon and oxygen, which

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* E. C. Bain concluded from x-ray investigations that there was a compound FeMo with hexagonal structure. Chem. & Met. 28:23 (1923)

precipitate at primary grain boundaries as compounds, impair the ductility of chromium alloys much more than of iron-base alloys.

MELTING, PURIFYING, AND CASTING CHROMIUM-BASE ALLOYS

At the time of deciding to investigate chromium-base alloys, it was expected that the alloys would be brittle. Therefore, it was necessary to choose a method of preparation which offered the greatest possibility of developing their maximum ductility. Only three methods were regarded as having possibilities for making useful shapes of chromium-base alloys:

1. Electrolytic deposition of the metals followed by a diffusion anneal.
2. Pressing powdered metals followed by sintering and hot working.
3. Melting and casting the metals.

In some early experiments, binary chromium alloys were made by electrolytic deposition followed by annealing, but to develop the separate procedures needed to deposit electrolytically the many alloys planned for study seemed too great a task for the time allotted. Furthermore, most electrolytic methods deposit metals contaminated with hydrogen and oxygen. The latter is often difficult to remove.

Pressing the powdered metals is preferred to electrolytic deposition, but this method cannot produce void-free (and thus stress-raiser-free) alloys unless the pressed and sintered shapes are hot worked or unless prohibitively long sintering times are used. It was reasonable to doubt that the alloys having high strength at 1600°F. could be hot worked by conventional means. Most metal powders contain injurious amounts of oxygen as oxides, which are difficult to remove in the solid. Finally, experience and equipment were lacking in this laboratory for working in powder metallurgy and inquiries for outside aid disclosed that laboratories equipped for powder metallurgy techniques were fully engaged on war problems.

Melting and casting seemed at the time to offer the most hope of making useful articles of chromium-base alloys, for there is the best opportunity of removal of impurities detrimental to ductility when the alloys are in the liquid state. Accordingly, this method was adopted. Up to now, no reason for questioning this decision has appeared to those associated with the investigation, although it has been reviewed at intervals when the melting and casting method encountered obstacles.

Molten chromium and chromium-rich alloys rapidly absorb nitrogen, oxygen, and carbon in amounts detrimental to ductility. Election of the melting and casting method requires evidently that these operations be done in vacuum or in inert (i.e., rare gas) atmosphere. Melting in an inert atmosphere will prevent absorption of nitrogen and oxygen and carbon, but oxygen and carbon will not be removed if present (and they always are present in deleterious amounts) in the melt unless the inert atmosphere is continuously replaced by purified rare gas. In vacuum, carbon and oxygen may be removed through the reaction

$$C+1/2\ O_2 \longrightarrow CO$$

If the concentration of carbon monoxide above the melt is low enough, the concentration of oxygen (for a given amount of carbon) may be reduced to any desired value, within certain obvious practical limitations. It was believed possible to set up for operation in vacuum in less time than needed to construct equipment for circulating and purifying rare gases. Also, the source of heat available (high-frequency electromagnetic induction) was low in power and this limitation made heat conservation an essential. Heat losses are a minimum in vacuum.

These are the reasons for melting in vacuum. Once the vacuum melting equipment is available, it is fairly easy to arrange to cast in vacuum.

The vacuum melting and casting method is applicable to all chromium-base alloys except those producing a vapor phase of such high pressure at the melting temperature that the loss of metal becomes excessive. Most metals of high melting point, which are the metals of greatest interest to this investigation, have low vapor pressure and produce alloys of low vapor pressure. Chromium itself is the most difficult of the refractory metals to melt in vacuum because of its high vapor pressure. Nevertheless, pure chromium can be melted and deoxidized in vacuum by the methods of this investigation if the power input during melting is high enough to perform the operation quickly. However, chromium is not strong enough at 1600°F. and thus not useful in gas turbine blades.

Five vacuum-melting and casting apparatus were constructed and operated to make simple shaped castings for this investigation. These have been described in unissued Progress Reports of Contract OEMsr-457, dated November 15, 1942, May 15, 1943, and November 15, 1943.

It is believed that the method of vacuum melting chromium-base alloys has been brought to a stage suitable for commercial use, with certain modifications. This is not so of the casting method, which is applicable only to simple shapes, since chromium alloys have so far been successfully cast (in this laboratory) in metal molds only. Both copper and low carbon steel have been used as mold materials. The most complex

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castings formed in metal molds were supercharger blades and shroudless gas turbine blades.

A few casting experiments were performed with silica sand molds. They were all unsuccessful, owing to melting of the silica. Melting of the silica molds occurred even when casting into molds at room temperature. One experiment indicated that chromium-base alloys could be cast into beryllia sand molds. Time was short, and so this part of the investigation (which ought to have included alumina and zirconia sand molds) had to be dropped. It should, however, be an important part of any future development of chromium-base alloys.

WELDING CHROMIUM-BASE ALLOYS

Chromium-base alloys cannot be welded by the techniques used to join cobalt-, iron-, and nickel-base alloys, because the chromium alloys become embrittled by absorption of nitrogen and oxygen and by formation of brittle compounds with the nickel in the welding rod. Experiments on the NRC-8 program under the supervision of Mr. Howard C. Cross, Supervisor of Heat Resisting Alloys Research, War Metallurgy Committee, and Messrs. J. D. Nisbet and J. A. Cameron, of General Electric Company, Fort Wayne, Indiana, indicate that chromium-base alloys must be welded in an inert atmosphere such as in the helium-shielded electric arc. The welding rod also should be a chromium-base alloy.

METHODS OF SHAPING CHROMIUM-IRON-MOLYBDENUM ALLOYS

Most of the chromium-base alloys must be ground, for they are too brittle to be shaped with cutting tools. Of the 900 heats of chromium

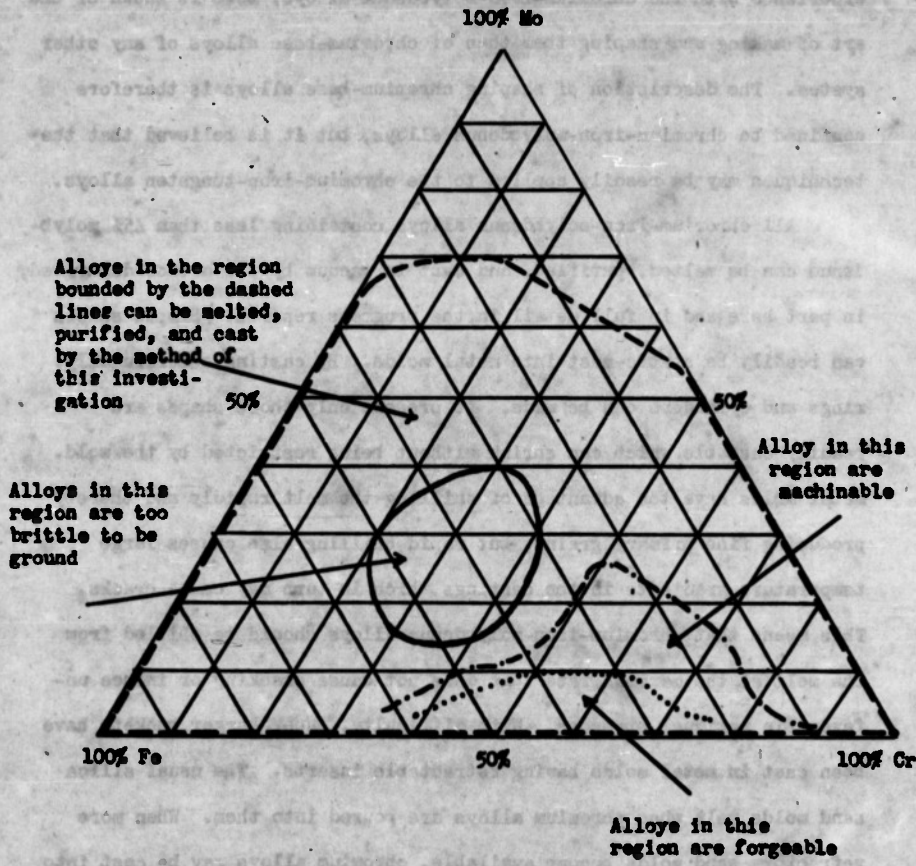

Figure 1

Methods of Shaping Cr-Fe-Mo Alloys

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alloys made, 200 were chromium-iron-molybdenum alloys. Owing to greater experience with the chromium-iron-molybdenum alloys, more is known of the art of making and shaping them than of chromium-base alloys of any other system. The description of shaping chromium-base alloys is therefore confined to chromium-iron-molybdenum alloys, but it is believed that the techniques may be readily applied to the chromium-iron-tungsten alloys.

All chromium-iron-molybdenum alloys containing less than 45% molybdenum can be melted, purified, and cast in vacuum by the method described, in part here and in full detail in the progress reports. Simple shapes can readily be static-cast into metal molds. By casting centrifugally, rings and cylinders can be made. At present only those shapes are readily castable which can shrink without being restricted by the mold. Metal molds have the advantage of chilling the melt rapidly and thereby producing fine primary grains, but rapid chilling also causes large temperature gradients in the castings which in turn may cause cracks. This means that chromium-iron-molybdenum alloys should be chilled from the melt at the maximum rate that does not cause cracking or induce unfavorable residual stresses. With difficulty, supercharger buckets have been cast in metal molds having retractable inserts. The usual silica sand molds melt when chromium alloys are poured into them. When more refractory sand molds become available, chromium alloys may be cast into more intricate shapes.

All the chromium-rich chromium-iron-molybdenum alloys may be formed by grinding, except those of compositions near 35Cr-25Mo-40Fe. Most of the chromium-iron-molybdenum alloys containing at least 15% iron, except those near 35Cr-25Fe-40Mo, can be turned and drilled with standard high speed steel tools. The cutting speeds are 34.0 ft/min (for turning) and 100 to 130 rpm (for drills from 1/4" to 1/2" diameter).

Some of the alloys containing more than 25% iron can be hot-formed at temperatures near 2700°F. (1480°C.). The possibility of hot forming even alloys containing less than 25% iron should be carefully considered in any future investigation of shaping chromium-base alloys.

The compositions which can be hot worked, those that can be machined with high speed steel tools, those that can be cast and formed by grinding, and those that can be formed by casting only are outlined on the ternary diagram of Figure 1. The diagram refers to ternary alloys containing not more than 0.10% carbon, not more than 0.05% oxygen, not more than 0.05% nitrogen, and not more than 0.50% silicon.

DISCUSSION

The original plan of work under Contract OEMsr-457 included the development of comparatively new metal systems rather than research to perfect the high temperature properties of commercial alloys of cobalt, iron, or nickel. At that time the opinion was held that to effect a large increase in the load-carrying ability of metals at high temperature, an alloy base should be selected which has a higher melting point than iron; for it was believed that the state of the knowledge of solids was such that no more reliable criterion of strength at high temperature was available than melting point. At the same time it was also considered improbable that pure metals would have as high strength at elevated temperatures as their alloys.

In consequence of these beliefs, the first alloys studied were tungsten-base, tungsten-chromium alloys, chromium being selected for corrosion resistance.

At 1600°F. the hardness of the tungsten-rich alloys was determined to be between 300 and 430 Vickers Pyramid Number. The hardness of several refractory iron-, nickel-, and cobalt-base alloys tested at 1500°F. was between 100 and 190 Vickers Pyramid Number. Purely as a matter of judgment, this difference in hot hardness was larger than was thought needed to bring about the desired substantial improvement in elevated temperature strength. It was found that the hardness of some of the chromium-rich, chromium-tungsten alloys at 1600°F. was about 300 Vickers Pyramid Number and, while not as high as the hardest tungsten-rich, chromium-tungsten alloys, were still appreciably harder than the iron-, cobalt-, and nickel-base alloys. The alloy containing 70% chromium and 30% tungsten, for example, with hardness of 338 Vickers Pyramid Number at 1600°F., seemed worthy of special study.

As a result of further examination of the chromium-rich, chromium-tungsten alloys, and upon noting that they were less brittle than the tungsten alloys, it was decided to direct the search for heat resistant alloys toward chromium-base alloys.

It is true that in making these decisions there was perhaps rather too much faith placed in the hot hardness test, but the exigency of the time necessitated this. Additional evidence in the stress-rupture test soon was forthcoming, to affirm the indications from the hot hardness test that chromium-base alloys had exceptionally high strength at 1600°F. However, the ductility of the early chromium-base alloys, as measured in the stress-rupture test at 1600°F. was very low (zero to 3% elongation). Ductility requirements of turbine blade materials were not definitely known in 1942, but from the best opinions obtainable it appeared that chromium-base alloys would be inadequate in shock resistance.

It became necessary to change the objective from a search for new high strength refractory alloys to improving the ductility of chromium-base alloys. Work on increasing the ductility of chromium-base alloys was carried principally along two separate lines: One was to reduce the amount of impurities; the other was through alloying. Both methods consist of investigating the effect of the composition variable upon ductility, the former involving development of special techniques and the latter, the art of alloying.

On the problem of purification, work was confined largely to elimination of chromium oxide, an impurity considered detrimental to ductility. Since, as previously stated, oxygen could be reduced by adding to the molten chromium-base alloy a chemically equivalent amount of carbon to form carbon monoxide and maintaining low partial pressure of carbon monoxide above the melt, the problem was essentially one of design of apparatus to efficiently carry off larger and larger volumes of gas at lower and lower pressures.

The amount of oxides or other non-metallic inclusions which a metal can tolerate, before the cause of rupture under simple tensile stress can be attributed to inclusions, is dependent upon the inherent ductility of the metal in the inclusion-free condition; the amount decreases as the inherent ductility decreases. The tolerance for non-metallic inclusions is further lowered if the metal is subjected to biaxial or tri-axial tensile stresses.

It is thus more rewarding to improve the purity of chromium-base alloys than, for instance, iron-base alloys.

As the oxide content of the alloys has been reduced, the ductility of the alloys has increased. At present the amount of oxide as measured microscopically is less than 0.10% by volume, but because the oxides usually reside at the grain boundaries, where they are especially effective as stress raisers, it is desirable to reduce them still further.

Oxide inclusions on crystal boundary surfaces in chromium-base alloys have been observed to form thin sheets 0.2 to 1.0 microns thick. A crystal facet (found on a fractured surface) with oxide plate attached, typical of an incompletely deoxidized heat is illustrated in Figure 2.

Some solid deoxidizers were added to molten chromium-base alloys in endeavors to reduce the oxygen content of the alloys. The deoxidizers added were zirconium, magnesium, manganese, aluminum and hydrogen. None was as efficient as pumping off oxygen as carbon monoxide. The experiments on deoxidation were, however, not complete, so that it cannot be concluded that oxygen removal is best performed by carbon.

The improvement of ductility by alloying chromium as a base required that a systematic survey of refractory alloys of chromium be made. Systematization comprised the study, first, of refractory binary alloys of chromium, and second, of refractory ternary alloys of chromium. This survey as planned is almost complete so far as binary alloys of chromium are concerned.

The most difficult problem faced in surveying alloys of chromium was that of compressing the survey to a size that could be handled by this

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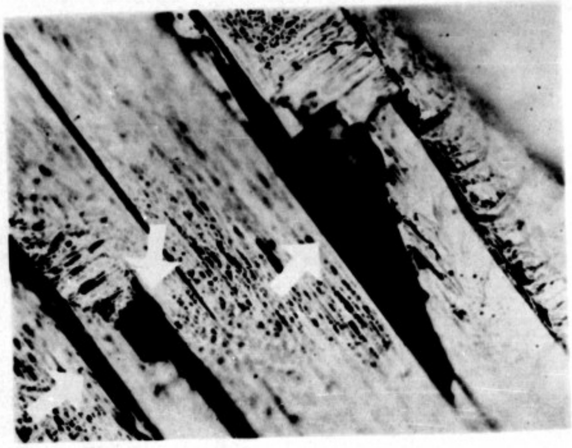

Figure 2 (#9018) Oxide Platesattached to a Crystal Facet (indicated by arrows). Unetched and unpolished surface prepared by fracturing. X500 laboratory and yet not miss the best chromium-base alloy.

In outlining the experimental work for the survey of refractory alloys of chromium, a number of assumptions were made. These assumptions are discussed in detail in the progress reports, but they will be repeated here so that extensiveness of the survey may be evaluated. The major assumptions were:

1. Elements should be selected that are likely to reduce the melting point of the alloy as little as possible, that is, high melting metals, preferably high melting transition metals. Metals having melting points below that of manganese (1260°F.) were arbitrarily excluded.
2. High temperature strength should not be obtained primarily by forming precipitation-hardening compounds with nitrogen or carbon, since these elements diffuse rapidly in the interstitial solid solutions which they form with chromium. The strengthening effect of nitrogen and carbon at high temperatures will thus be of a temporary nature.
3. Metals costing more than one dollar per gram would be too scarce to consider for gas turbine parts.
4. The investigation should be confined to alloys containing at least 50 per cent chromium, in order that the alloys inherit the valuable properties of chromium, corrosion resistance, high melting point, and low density.

These assumptions limited the binary alloy investigation to thirteen systems.

From the investigation of the binary systems, it was concluded that the Cr-Fe, Cr-Ni, and Cr-Co alloys were the most ductile at 1600°F. and that the Cr-Cb, Cr-Mo, Cr-Ta, and Cr-W alloys were the strongest. But the ductile binary alloys were weak and the strong alloys, brittle.*

From the ternary investigation, alloys in five systems were found having a better combination of strength and ductility than the best binary alloys. The five systems are: Cr-Fe-Mo, Cr-Fe-W, Cr-Fe-Ta, Cr-Co-Mo,

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* It is of interest to record that the Cr-Ti and Cr-Ta alloys exhibited extraordinary resistance to abrasion.

and Cr-Co-W. The Cr-Co-Mo and Cr-Co-W alloys were soon abandoned because of their troublesome brittleness at room temperature. The Cr-Fe-Ta alloys were also abandoned, because their properties were inferior to those of alloys of the other four ternary systems and because the Cr-Fe-Ta alloys are the most costly. The Cr-Fe-W and the Cr-Fe-Mo alloys were then studied in some detail. From this study it was concluded, upon considering only alloys having a minimum of 5% reduction of area in the stress-rupture test at 1600°F., that the best Cr-Fe-Mo alloy (No. 469) was slightly better than the best Cr-Fe-W alloy (No. 382). Alloy No. 469 supported a stress of 30,000 psi at 1600°F. for 291 hours, with 5% elongation and 5% reduction of area. Alloy No. 382 supported a stress of 24,000 psi at 1600°F. for 110 hours, with 7% elongation and 5.5% reduction of area. The density of Alloy No. 469 is 4.8% less than that of Alloy No. 382. The Cr-Fe-W alloys generally resisted oxidation at 1600°F. better than the Cr-Fe-Mo alloys, but there was no evidence that the Cr-Fe-Mo alloys failed in the stress-rupture test because of oxidation.

On the basis of stress-rupture properties, density, availability, and cost of the constituent metals, after testing 29 chromium-iron-molybdenum and 39 chromium-iron-tungsten alloys, the Cr-Fe-Mo system was selected for extensive investigation, which pointed out that alloys of the most useful combination of strength would be found not too far from the composition line joining the 60Cr-25Fe-15Mo alloy with the 60Cr-15Fe-25Mo alloy.

At this point it would be proper to choose two or three alloys in the composition range just outlined and conduct intensive studies of the effects of special variables on their properties. These special variables would, for example, be heat treatment, grain size, hot working, residual elements, such as carbon, silicon, oxygen, and nitrogen. Such a program was initiated, but not completed, just before the whole investigation was terminated.

The program has, at the time of writing this report, provided sufficient information to tempt the author to make the following statements, which, if true, will aid future investigations of chromium-base alloys:

For optimum combination of strength and ductility of the 60Cr-25Fe-15Mo alloy at 1350°F.,

1. The carbon content should be about 0.05%.
2. The silicon content should be about 0.5%.
3. The oxygen content should be a minimum.
4. The nitrogen content should be a minimum.
5. The grain size should be the smallest attainable.
6. If used in the form of castings, the alloy should be quenched from the melt (i.e., chill cast). No other heat treatment has yet been discovered that gives superior properties.

For optimum combination of strength and ductility of the 60Cr-15Fe-25Mo alloy at 1600°F.,

1. The carbon content should be less than 0.05%.
2. The silicon content should be less than 0.2%.
3. The oxygen content should be a minimum.
4. The nitrogen content should be a minimum.
5. The grain size should be the smallest attainable.
6. If used in the form of castings, the alloy should be quenched from the melt (i.e., chill cast), then annealed 90 hours at 1600°F.

The survey of ternary alloys of chromium was not complete. Toward the end of the investigation, it was decided to narrow the field of work by assuming that the second metal of the ternary systems should be iron. This assumption was made because of lack of time, but it can also be rationalized by the facts:

1. Iron, more than any other element tested, improves the ductility of chromium.
2. The addition of iron permits the use of ferrochromium.
3. Iron is similar to chromium and therefore will not reduce the melting point greatly.

SUMMARY AND CONCLUSIONS

Methods of melting, deoxidizing, and shaping chromium-base alloys have been developed.

Summary and Conclusions

That portion of thirteen binary and nine ternary systems of chromium containing more than 50% chromium have been explored in a necessarily preliminary manner. Only two of the systems were investigated in detail. These two were the Cr-Fe-Mo and Cr-Fe-W systems, and they were studied because in stress-rupture tests at 1600°F. the Cr-Fe-Mo and Cr-Fe-W alloys gave the highest strengths with measurable ductility.

That the best chromium-base alloys contained at least 15% iron is advantageous, since this permits the use of ferro-alloys and makes it unnecessary to keep carbon contents below 0.03% and silicon contents below 0.50%.

Considering their properties, their cost, and the availability in war time of the constituent metals, the Cr-Fe-Mo alloys in the composition range 60Cr-25Fe-15Mo to 60Cr-15Fe-25Mo appear most worthy of further research. In this range two alloys are notable, the 60Cr-15Fe-25Mo for use at 1600°F. and the 60Cr-25Fe-15Mo for use at 1350°F. The properties of these two alloys are summarised in Table VI and Figure 3.

The ductility of chromium-base alloys was improved as they were made purer and finer grained. Still, none of the alloys (in the as-cast condition) exhibited measurable ductility in a tensile test at room temperature. It is believed that further research on the alloys will result in an increase in their plasticity, but it is unlikely that they can be made as shock-resistant as iron-, nickel-, or cobalt-base alloys, simply on the basis of melting point.

It is important, therefore, that any machine element to be made of chromium-base alloys be designed with smooth flowing curves and that the part be made without stress-raising tool marks, without unfavorable residual stresses, but where possible with favorable residual stresses.

Some of the chromium-base alloys are resistant to abrasion; some resist the attack of acids. Alloys of chromium may therefore have uses other than heat resistance.

TABLE VI

Properties of 60Cr-25Fe-15Mo and 60Cr-15Fe-25Mo Alloys

	Hardness (Vickers Pyramid Number)
At Room Temperature	
60Cr-25Fe-15Mo, As Cast	455-579
60Cr-15Fe-25Mo, As Cast	498
Held 24 hrs. at 1600°F.	480
Held 48 hrs. at 1600°F.	488
Held 90 hrs. at 1600°F.	478
Held 130 hrs. at 1600°F.	563
Held 4 hrs. at 2400°F.	592
Held 20 hrs. at 2400°F.	624
Held 44 hrs. at 2400°F.	626
At 1112°F.	
60Cr-25Fe-15Mo, As Cast	430
60Cr-15Fe-25Mo, As Cast	430
At 1292°F.	
60Cr-25Fe-15Mo, As Cast	376
60Cr-15Fe-25Mo, As Cast	396
At 1600°F.	
60Cr-25Fe-15Mo, As Cast	192-220
60Cr-15Fe-25Mo, As Cast	296
At 1700°F.	
60Cr-25Fe-15Mo, As Cast	141-180
60Cr-15Fe-25Mo, As Cast	274

Machinability

60Cr-25Fe-15Mo: Can be turned and drilled with high speed tools.
60Cr-15Fe-25Mo: Can be machined with carboloy tools and ground.

Forgeability

No successful forging has been performed to date on either alloy.

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TABLE VI (Cont.)

Stress-Rupture Properties

Heat No.	Temp. °F.	Stress psi.	Time for Rupture	% El	% RA	Remarks
60Cr-25Fe-15Mo						
554-2	1350	50,000	1414 Hrs.	8	6.2	
612-2	1350	50,000	484 "	9	9	
634-1	1350	50,000	985 "	5	5	0.70% Si
679-2	1350	55,000	611 "	5	6	
679-1	1350	63,800	182 "	5	0	
554-1	1600	20,000	132 "	22.0	24.8	
621	1600	20,000	70.5 "	14.0	14.5	0.307% C
60Cr-15Fe-25Mo						
469-1	1700	20,000	76 "	5.5	5.0	
469-4	1600	20,000	1042 "	9	12	
469-2	1600	24,000	478 "	5.0	5.0	
469-3	1600	30,000	291 "	5.0	5.0	
635-1	1600	30,000	290 "	9.5	7.6	0.13% C
635-2HT	1600	26,500	472 "	9.0	8.6	Test interrupted @ 276 hrs.
636-1	1600	30,000	132 "	4.0	8.5	
636-2HT	1600	30,000	316.5 "	3.0	2.4	Test interrupted @ 248 hrs.
667-2	1600	30,000	336 "	4.0	1.2	0.51% Si. Held 90 h. @ 1600°F.
668-2	1600	30,000	430.5 "	6.0	6.3	Held 90 hrs. @ 1600°F.
668-3	1600	30,000	145 "	8.0	7.4	Held 60 hrs. @ 1800°F.
613-1	1600	37,500	65 "	1.0	1.2	
613-2	1600	35,000	371 "	5.0	3.8	

Density

60Cr-25Fe-15Mo: 7.63 g/cc   60Cr-15Fe-25Mo: 7.87 g/cc

Tensile Strength @ 1350°F.

60Cr-25Fe-15Mo: 99,700 and 103,500 psi

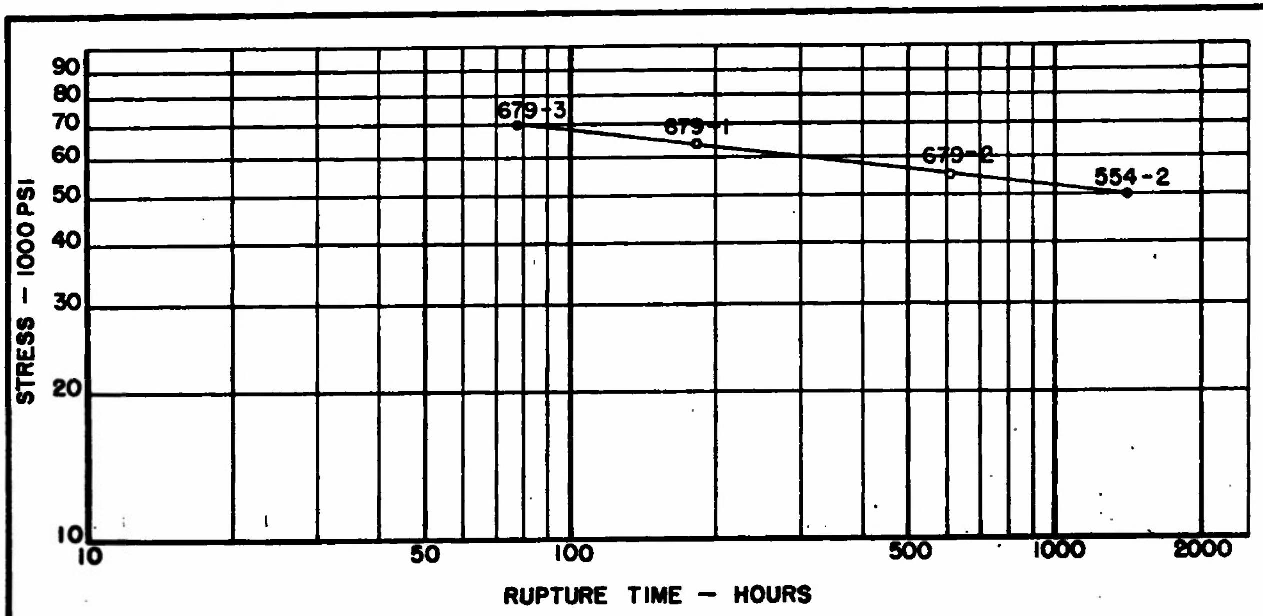

FIGURE 3

STRESS – RUPTURE TIME CURVE
FOR THE 60 Cr-25Fe-15Mo ALLOY AT 1350°F

APPENDIX I

CHEMICAL ANALYSIS DATA AND DESCRIPTIVE NOTES ON THE ALLOYS MENTIONED IN THIS REPORT

Heat* No.	
58	0.19% C, 58.88% Cr, bal. W
73	0.026% C, 0.59% Si, 68.7% Cr, 0.033% Zr, bal. W
91	0.046% C, 0.30% Si, 58.04% Cr, 24.39% W, 16.22% Fe
106	0.23% C, 0.09% Si, 77.79% Cr, 20.44% W, 1.07% Fe
123	0.025% C, 0.447% Si, 67.83% Cr, 29.28% W, 0.21% Fe
162	0.051% C, 15.36% Fe, 59.98% Cr, 23.05% W, 0.17% Al
166	0.024% C, 60.14% Cr, 23.67% W, 15.30% Fe
167	0.095% C, 62.17% Cr, 22.08% W, 14.74% Fe. Heat treated 164 hours at 1600°F.
168C	0.112% C, 58.33% Cr, 12.01% W, 27.92% Fe. Heat treated 164 hours at 1600°F.
168D	Same heat as 168C. As cast
169	0.027% C, 67.73% Cr, 23.18% W, 8.46% Fe. Heat treated 164 hours at 1600°F.
177A	0.05% C, 77.96% Cr, 6.20% W, 14.71% Fe
212-M1	0.026% C, 0.63% Si, 46.44% Cr, 26.53% W, 22.33% Fe, 2.41% Mo
214-M1	0.05% C, 0.68% Si, 44.51% Cr, 28.32% W, 22.93% Fe, 2.74% Mo
216-M1	0.029% C, 0.57% Si, 45.01% Cr, 22.04% Fe, 28.81% W, 2.74% Mo
239-M1	0.018% C, 0.52% Si, 57.78% Cr, 19.58% W, 19.79% Fe
243-M1	0.018% C, 0.61% Si, 55.42% Cr, 21.33% W, 20.44% Fe, 1.98% Mo
246-M1	0.018% C, 0.56% Si, 55.95% Cr, 21.12% W, 20.08% Fe, 2.00% Mo
249-M1	0.016% C, 0.52% Si, 58.48% Cr, 19.74% W, 19.10% Fe, 1.89% Mo
256*	0.39% C, 0.20% Si, 46.03% Cr, 53.76% Fe
257	0.071% C, 0.30% Si, 47.92% Cr, 47.97% Ni, 2.80% Fe
258	0.245% C, 0.28% Si, 71.95% Cr, 26.69% Ni, 0.29% Fe
261	0.020% C, 56.05% Cr
262	0.327% C, 0.21% Si, 79.96% Cr, bal. Co
266	0.008% C, 0.13% Si, 19.22% Mo, 79.71% Cr, 0.17% Fe
267	0.008% C, 0.17% Si, 61.50% Cr, 0.19% Fe, bal. Mo
268	0.015% C, 0.09% Si, 9.51% Mo, 89.38% Cr, 0.24% Fe
269	0.040% C, 99.25% Cr
271	0.179% C, 0.09% Si, 73.52% Cr, 26.50% Fe
272	0.095% C, 0.49% Si, 61.14% Cr, 17.54% W, 18.65% Fe, 1.77% Mo
273	0.254% C, 0.14% Si, 65.12% Cr, 31.80% Co, 0.36% Fe, 0.77% Ni
307	0.032% C, 0.56% Si, 59.95% Cr, 19.48% W, 19.32% Fe
309	0.027% C, 0.63% Si, 67.27% Cr, 11.39% W, 20.11% Fe
311	0.026% C, 0.56% Si, 61.57% Cr, 18.05% W, 19.75% Fe
312	0.071% C, 0.61% Si, 61.46% Gr, 13.70% W, 23.45% Fe

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* Heats 58 through 177A were static cast. Heats 256 and beyond were centrifugally cast.

Heat No.	
313	0.021% C, 0.42% Si, 69.26% Cr, 14.97% W, 15.22% Fe
313-1	Same heat as 313.
313-2	Same heat as 313.
314	0.19% C, 0.55% Si, 58.22% Cr, 19.78% W, 20.76% Fe
315	0.016% C, 0.31% Si, 60.93% Cr, 26.63% W, 11.63% Fe
316	0.007% C, 0.20% Si, 73.68% Cr, 20.28% W, bal. Fe
317	0.018% C, 0.43% Si, 49.13% Cr, 34.43% W, 15.54% Fe
319	0.066% C, 0.66% Si, 55.17% Cr, 19.76% W, 23.74% Fe
320	0.098% C, 0.60% Si, 50.09% Cr, 24.37% W, 24.58% Fe
321	0.092% C, 0.51% Si, 51.90% Cr, 26.53% W, 20.53% Fe
322	0.036% C, 0.16% Si, 52.23% Cr, 21.92% W, 1.09% Fe, 24.19% Ni, 0.013% Zr
324	0.175% C, 57.04% Cr, 12.65% Ni, 27.71% W, 1.17% Cu
326	0.142% C, 0.21% Si, 67.23% Cr, 21.70% W, 0.27% Fe, 10.22% Ni
327	0.261% C, 0.12% Si, 60.37% Cr, 20.80% Ni, 17.67% W, 0.33% Fe
328	0.187% C, 0.18% Si, 76.05% Cr, 7.73% Ni, 15.53% W, 0.24% Fe
330	0.209% C, 0.13% Si, 70.51% Cr, 13.90% W, 14.69% Ni, 0.25% Fe
335	0.085% C, 0.51% Si, 46.68% Cr, 21.30% W, 31.27% Fe
341	0.186% C, 71.82% Cr, 27.13% Ta, 0.17% Fe
342	0.126% C, 82.50% Cr, 15.95% Ta, 0.10% Fe
343	0.161% C, 0.26% Si, 87.24% Cr, 10.50% Pt.
347	0.224% C, 68.91% Cr, 30.82% Cb
350	0.032% C, 0.11% Si, 77.03% Cr, 15.95% W, 6.89% Ni, 0.18% Fe
351	0.040% C, 0.07% Si, 50.29% Cr, 30.00% W, 19.13% Ni, 0.24% Fe
354	0.141% C, 84.99% Cr, 14.23% Cb
356	0.063% C, 0.61% Si, 58.20% Cr, 15.34% W, 25.02% Fe
363	0.057% C, 0.55% Si, 64.35% Cr, 13.81% Mo, 20.69% Fe
370	0.032% C, 88.30% Cr, 11.07% Ta
373	0.003% C, 0.124% Si, 59.94% Cr, 13.59% Co, 25.88% W
374	0.153% C, 0.06% Si, 58.20% Cr, 13.71% Co, 27.47% W
375	0.127% C, 0.16% Si, 57.88% Cr, 13.12% Co, 28.54% W
376	0.210% C, 0.68% Si, 58.31% Cr, 18.33% W, 22.64% Co
377	0.005% C, 0.169% Si, 66.13% Cr, 22.50% W, 18.81% Co
379	0.032% C, 0.154% Si, 71.39% Cr, 12.87% W, 15.09% Co
381	0.014% C, 0.07% Si, 76.42% Cr, 15.54% W, 8.07% Co
382	0.070% C, 0.033% Si, 62.01% Cr, 19.23% Fe, 18.62% W
383	0.035% C, 0.18% Si, 87.70% Cr, 10.99% Pt
384	0.063% C, 89.43% Cr, 9.98% Cb
386	0.006% C, 0.215% Si, 82.95% Cr, 16.20% Mo, 0.052% Fe
387	0.043% C, 0.589% Si, 57.10% Cr, 20.70% W, 21.06% Fe
387-1	Same heat as 387.
387-2	Same heat as 387.
389	0.169% C, 0.124% Si, 87.86% Cr, 9.12% V, 0.78% Fe, 1.62% W
390	0.171% C, 0.129% Si, 0.296% Fe, 0.178% W, 78.53% Cr, 20.06% V
392	0.017% C, 0.14% Si, 61.14% Cr, 16.92% Co, 20.93% W, 0.23% Fe
393	0.019% C, 0.089% Si, 84.79% Cr, 12.91% Ni, 0.077% Fe, 1.07% W, 0.689% Co
396	0.064% C, 0.232% Si, 0.285% Fe, 81.74% Cr, 16.72% V

Heat No.	
399	0.024% C, 0.575% Si, 56.96% Cr, 20.45% Fe, 21.41% W
399-1	Same heat as 399.
399-2	Same heat as 399.
399-3	Same heat as 399.
399-4	Same heat as 399. After stress-rupture test, 324 hrs. at 20,000 psi.
400	0.008% C, 0.22% Si, 51.67% Cr, 10.76% Fe, 36.48% W
403	0.019% C, 0.20% Si, 86.00% Cr, 12.37% Co, 0.17% Fe
404	0.045% C, 0.51% Si, 58.53% Cr, 19.59% Fe, 20.07% Mo
407	0.021% C, 0.497% Si, 50.69% Cr, 29.77% W, bal. Fe
408	0.041% C, 0.59% Si, 51.55% Cr, 19.91% W, bal. Fe
409	0.010% C, 0.48% Si, 66.12% Cr, 14.54% W, 18.85% Fe (by difference)
412	0.021% C, 0.68% Si, 61.73% Cr, 10.77% W, bal. Fe
414	0.062% C, 0.55% Si, 55.68% Cr, 15.10% Mo, bal. Fe
416	0.063% C, 0.58% Si, 51.99% Cr, 23.78% Mo, 23.59% Fe
418	0.027% C, 0.25% Si, 69.05% Cr, 17.88% Mo, bal. Fe
419	0.021% C, 0.25% Si, 62.36% Cr, 27.78% Mo, bal. Fe
419-1	Same heat as 419.
419-2	Same heat as 419.
420	0.032% C, 0.60% Si, 64.78% Cr, 10.13% Mo, bal. Fe
421	0.156% C, 0.65% Si, 80.77% Cr, 4.86% U, bal. Fe
422	0.181% C, 9.68% Zr, bal. Cr
424	0.124% C, 0.07% Si, 90.57% Cr, 9.12% Ti
428	0.052% C, 0.24% Si, 0.06% Be, bal. Cr
429	0.035% C, 0.18% Si, 6.83% Ti, bal. Cr.
430	0.030% C, 8.72% Zr, bal. Cr
434	0.093% C, 43.04% Cr, 36.17% Mo, bal. Fe
434-1	Same heat as 434.
434-2	Same heat as 434.
440	0.017% C, 0.13% Si, 12.89% Cr, 22.44% Mo, bal. Fe
441	0.038% C, 0.02% Si, 61.14% Cr, 19.03% Mo, 19.57% Co
441-1	Same heat as 441.
441-2	Same heat as 441.
444-1	0.019% C, 0.01% Si, 56.65% Cr, 38.46% Mo, bal. Fe
444-2	Same heat as 444-1.
445	0.025% C, 0.01% Si, 50.02% Cr, 40.60% Mo, bal. Fe
446	0.047% C, 0.03% Si, 71.40% Cr, 4.95% Mo, bal. Co
447	0.091% C, 0.23% Si, 88.77% Cr, 5.90% Mo, bal. Co
448	0.126% C, 60.29% Cr, 20.30% Fe, 19.78% Ta
449	0.112% C, 66.48% Cr, 25.10% Fe, 8.52% Ta
452	0.025% C, 0.033% Si, 69.98% Cr, 18.87% Mo, 10.56% Co
461	0.097% C, 51.60% Cr, 24.13% Ta, bal. Fe
463	0.077% C, 56.32% Cr, 14.74% Ta, bal. Fe
469	0.027% C, 0.10% Si, 59.86% Cr, 25.59% Mo, bal. Fe
469-1	Same heat as 469.
469-2	Same heat as 469.
469-3	Same heat as 469.
469-4	Same heat as 469.

Appendix I

Heat No.	
470	0.075% C, 0.36% Si, 51.12% Cr, 14.92% Mo, bal. Fe
470-HT	Same heat as 470. Held 130 hrs. at 1600°F., air cooled.
471	0.038% C, 0.37% Si, 60.53% Cr, 5.02% Mo, 34.04% Fe
471-HT	Same heat as 471. Held 130 hrs. at 1600°F., air cooled.
472	0.020% C, 0.03% Si, 56.34% Cr, 33.58% Mo, bal. Co
476-2	0.066% C, 0.38% Si, 56.42% Cr, 15.08% Mo, bal. Fe
476-HT	Same heat as 476-2. Held 160 hrs. at 1600°F., air cooled.
478	0.019% C, 0.24% Si, 50.66% Cr, 4.99% Mo, bal. Fe
478-HT	Same heat as 478. Held 162 hrs. at 1600°F., air cooled.
479-1	0.040% C, 0.37% Si, 56.42% Cr, 10.19% Mo, bal. Fe
479-2	Same heat as 479-1. Held 168 hrs. at 1600°F.
485-HT	0.075% C. Aged 72 hrs. at 1600°F., air cooled.
518-1	0.016% C, 0.04% Si, 58.43% Cr, 15.46% Mo, bal. Fe
518-HT	Same heat as 518-1. Held 90 hrs. at 1600°F.
522	0.50% C, 0.17% Si, 58.60% Cr, 25.71% Fe, 15.47% Mo
526	0.101% C, 0.06% Si, 58.41% Cr, 15.43% Mo, bal. Fe
528	0.036% C, 0.04% Si, 54.51% Cr, 10.23% Mo, bal. Fe
528-HT	Same heat as 528. Held 90 hrs. at 1600°F.
530	0.040% C, 0.03% Si, 59.14% Cr, 9.82% Mo, bal. Fe
530-1	Same heat as 530.
530-2	Same heat as 530.
531	0.048% C, 0.07% Si, 64.95% Cr, 5.14% Mo, bal. Fe
533	0.032% C, 0.06% Si, 49.51% Cr, 9.98% Mo, bal. Fe
534	0.016% C, 0.11% Si, 49.26% Cr, 14.68% Mo, bal. Fe
534-1	Same heat as 534.
534-2	Same heat as 534.
535	0.011% C, 0.05% Si, 49.44% Cr, 20.40% Mo, bal. Fe
537	0.030% C, 0.06% Si, 54.56% Cr, 20.52% Mo, bal. Fe
537-1	Same heat as 537.
537-2	Same heat as 537.
539	0.011% C, 0.04% Si, 54.18% Cr, 25.72% Mo, bal. Fe
540	0.013% C, 0.05% Si, 49.44% Cr, 5.71% Mo, bal. Fe
543	0.016% C, 0.04% Si, 70.04% Cr, 4.57% Mo, bal. Fe
545	0.037% C, 0.03% Si, 55.00% Cr, 5.08% Mo, bal. Fe
546-1	0.032% C, 0.04% Si, 58.91% Cr, 5.19% Mo, 35.83% Fe
547	0.047% C, 0.23% Si, 69.40% Cr, 10.05% Mo, bal. Fe
548	0.035% C, 0.04% Si, 70.00% Cr, 15.42% Mo, bal. Fe
549	0.048% C, 0.10% Si, 64.55% Cr, 20.51% Mo, bal. Fe
550	0.027% C, 0.08% Si, 40.54% Cr, 5.19% Mo, bal. Fe
552	0.013% C, 0.18% Si, 47.90% Cr, 31.87% Mo, bal. Fe
553	0.002% C, 0.06% Si, 30.88% Cr, 5.53% Mo, bal. Fe
554-1	0.037% C, 0.57% Si, 59.43% Cr, 15.00% Mo, bal. Fe
554-2	Same heat as 554-1.
556	0.005% C, 0.26% Si, 3.10% Zr, bal. Cr
557	0.019% C, 0.37% Si, 2.40% Be, bal. Cr
558	0.011% C, 0.36% Si, 5.18% Th, bal. Cr
559	0.043% C, 1.20% Si, 58.84% Cr, 15.22% Mo, bal. Fe
561	0.221% C, 0.25% Si, 59.54% Cr, 25.36% Fe, 14.63% Mo

Heat No.	
567	0.013% C, 0.15% Si, 60.19% Cr, 20.16% Fe, 19.49% Ni
568	0.009% C, 0.06% Si, 59.67% Cr, 20.56% Fe, 19.70% Co
571	0.095% C. Two liters of nitrogan (at atmospheric temperature and pressure) were added after the heat was fully deoxidized, to give a final pressure of 44 mm. in the entire system for 2-1/2 minutes. Then the system was pumped to 0.210 mm. pressure before casting.
599	0.105% C, 0.29% Si, 58.57% Cr, 15.09% Mo, bal. Fe
608	0.033% C, 0.14% Si, 61.96% Cr, 8.73% Mo, bal. Fe
612-1	0.013% C, 0.13% Si, 58.86% Cr, 15.89% Mo, bal. Fe
612-2	Same as heat 612-1.
613-1	0.049% C, 0.31% Si, 57.59% Cr, 27.62% Mo, bal. Fe
613-2	Same as heat 613-1.
618-1	0.011% C, 0.26% Si, 59.03% Cr, 20.31% Mo, bal. Fe
618-2HT	Same heat as 618-1. Held 90 hrs. at 1600°F.
620	0.013% C, 0.58% Al
621	0.307% C, 0.23% Si, 57.14% Cr, 16.26% Mo, bal. Fe
623	0.19% C, 9.13% Cb, bal. Cr
629	0.010% C, 0.22% Si, 42.72% Cr, 10.17% Mo, bal. Fe
630	0.016% C, 0.19% Si, 42.52% Cr, 21.01% Mo, bal. Fe
632	0.064% C, 0.27% Si, 57.18% Cr, 27.68% Mo, bal. Fe
634-1	0.103% C, 0.70% Si, 59.09% Cr, 15.56% Mo, bal. Fe
634-2	Same as heat 634-1. Held 90 hrs. at 1600°F.
635-1	0.129% C, 0.11% Si, 60.44% Cr, 25.10% Mo, bal. Fe
635-2	Same heat as 635-1. Held 90 hrs. at 1600°F.
636-1	0.157% C, 0.50% Si, 60.55% Cr, 24.97% Mo, bal. Fe
636-2	Same heat as 636-1. Held 90 hrs. at 1600°F.
655-1	0.016% C, 0.19% Si, 59.80% Cr, 14.76% Mo, bal. Fe
655-2HT	Same heat as 655-1. Held 90 hrs. at 1600°F.
655-3HT	Same heat as 655-1. Held 50 hrs. at 1800°F.
657-1	0.082% C, 0.19% Si, 60.70% Cr, 14.81% Mo, bal. Fe
657-2	Same heat as 657-1. Held 90 hrs. at 1600°F.
667-1	0.021% C, 0.51% Si, 59.32% Cr, 25.40% Mo, bal. Fe
667-2HT	Same heat as 667-1. Held 90 hrs. at 1600°F.
668-1	0.032% C, 0.10% Si, 59.33% Cr, 25.18% Mo, bal. Fe
668-2HT	Same heat as 668-1. Held 90 hrs. at 1600°F.
668-3HT	Same heat as 668-1. Held 60 hrs. at 1800°F.
678-1	0.030% C, 0.19% Si, 65.49% Cr, 9.67% Mo, bal. Fe
678-2	Same as heat 678-1.
679-1	0.022% C, 0.70% Si, 60.44% Cr, 14.63% Mo, bal. Fe
679-2	Same as heat 679-1.
679-3	Same as heat 679-1.
L-5VP	0.018% C, 0.071% Si, 57.12% Cr, 20.06% Mo, bal. Fe
L-64	0.058% C, 0.14% Si, 58.70% Cr, 5.45% Mo, 1.75% W, bal. Fe

APPENDIX II

LIST OF SEMIANNUAL AND CUMULATIVE PROGRESS REPORTS

In addition to the monthly progress reports, the following semiannual and cumulative progress reports have been issued by Climax Molybdenum Company, under Contract OEMsr-457:

First Semiannual Progress Report, November 15, 1942, by Robert M. Parke (Unissued).

Climax Molybdenum Company is cooperating on NRC-8 by preparing heats of iron-, nickel-, and cobalt-base alloys, by performing hardness tests at elevated temperatures, and by investigation of tungsten-base alloys. On the basis of hardness and oxidation resistance at 1600°F., alloys containing 60 to 90% chromium, balance tungsten, look promising. These alloys melt at about 3500°F. Melting must be done in vacuum or possibly in an atmosphere of hydrogen or a noble gas. Methods of making a casting large enough to prepare a stress-rupture specimen have been developed. Stress-rupture specimens of chromium-tungsten alloys will be submitted to test within 30 days.

Progress Report, NDRC Research Project NRC-8, OEMsr-457, Heat-Resisting Metals for Gas Turbine Parts (N-102), from November 15, 1942, to May 15, 1943, by Robert M. Parke (Unissued).

The results of stress-rupture tests show that chromium-tungsten-iron alloys should be considered in selecting materials from which to make blades for gas turbines operating at 1600°F. A method for vacuum centrifugal casting these alloys in the form of turbine blades is now being developed.

Progress Report, NDRC Research Project NRC-8, OEMsr-457, Heat-Resisting Metals for Gas Turbine Parts (N-102), from May 15, 1943, to November 15, 1943, by Robert M. Parke (Unissued).

Additional stress-rupture data on chromium-base alloys are reported. A few General Electric Type B-2 supercharger blades have been centrifugally cast in vacuum. Improved apparatus for centrifugally casting turbine blades in vacuum is described. Vacuum centrifugally cast stress-rupture specimens of compositions selected to guide the investigation toward the answer to the problem of improving ductility have been prepared.

Progress Report, NDRC Research Project NRC-8, OEMsr-457, Heat-Resisting Metals for Gas Turbine Parts (N-102), from November 15, 1943 to May 15, 1944, by Robert M. Parke and Frederick P. Bens (Unissued).

About 100 General Electric Type B-2 Supercharger Blades of chromium-base alloys have been made in a newly designed apparatus for melting and centrifugal casting in vacuum. These blades are to be tested in a supercharger.

Chromium alloys of improved ductility have been prepared, but the procurement of ductility was accompanied, as usual, by some loss in strength. The most ductile alloy contained 55% chromium, 15% molybdenum and 29% iron. In a stress-rupture test at 20,000 psi and 1600°F., its time for rupture was 60 hours, elongation 20.0% and reduction of area 29.2%.

5th Semiannual, or 30th Monthly, Progress Report, NDRC Research Project NRC-8, Heat-Resisting Metals for Gas Turbine Parts (N-102), from May 15, 1944, to November 15, 1944, by Frederick P. Bens (Unissued).

Various physical property studies on chromium-base alloys have been completed or are now in progress. Included are: weldability, room temperature properties, effect of heat treatment, corrosion resistance, forgeability, and properties at elevated temperatures. The techniques for the deoxidation and purification of chromium-base alloys have been improved.

Progress Report, NDRC Research Project NRC-8, OEMsr-457, Heat-Resisting Metals for Gas Turbine Parts (N-102), February 26, 1945, by Robert M. Parke (cumulative report of three years' work on Contract OEMsr-457). OSRD Report 5044, Serial No. M-510. May 7, 1945.

A new class of metallic alloys, in which chromium is the alloy base, is being investigated. The chromium-rich portions of thirteen binary systems of chromium and nine ternary systems of chromium have been surveyed. On considering the availability of the constituent metals and the physical properties and formability of the alloys, it is concluded at this time that the most promising alloys for heat resistance are the chromium-rich, chromium-iron-molybdenum alloys. These alloys can be precipitation hardened.

Methods of forming useful articles of the alloys have been developed. The properties of the alloys are similar to those of chromium. Compared with the alloys of cobalt, or iron, or of nickel, they are chemically inert, they have high strength at high temperature, they have low densities, and they have high melting points. The strongest alloy at 1600°F. contains 50% chromium, 9% iron, and 41% molybdenum. In a stress-rupture test at 1600°F., it supported a stress of 24,000 psi for 1246 hours. The most ductile alloy at 1600°F. contains 50% chromium, 40% iron, and 10% molybdenum. In a stress-rupture test at 1600°F., it supported a stress of 20,000 psi for 3-3/4 hours, with 88% elongation and 56.1% reduction of area. The alloy believed to have the optimum properties for turbine blades contains 60% chromium, 15% iron, and 25% molybdenum. It supported a stress of 30,000 psi for 291 hours, with 5.0% elongation and 5.0% reduction of area.

The alloys are being developed to serve at 1600°F. as parts for gas turbines. They may be useful in other heat engines and other objects.

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SECTION: Misc. Non-Ferrous Metals and Alloys (12)
CROSS REFERENCES: Non-ferrous alloys - Thermal properties (66762); Strength of materials (90750); Chromium alloys - Manufacture (23255);*

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*Turbines - Materials (95515)

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*Chromium alloys

*Gas turbines

Heat resistant metals

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